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Biological and Environmental Efficiency of High Producing  
Dairy Systems through application of Life Cycle Analysis

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Thesis submitted for the degree of Doctor of Philosophy



The University of Edinburgh

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### ***Declaration***

I declare that I have composed this thesis, and that the work described is my own. All assistance received is acknowledged. The work has been submitted for no other qualification.

Stephen Alexander Ross

14<sup>th</sup> July 2014

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### ***Published material***

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\*All published material and proceedings are presented in Appendix

## ***Abstract***

Dairy production systems are an important global contributor to anthropogenic greenhouse gas (GHG) emissions including methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>). Due to the role GHG play in climate change, it is important to investigate ways to minimise their global warming potential (GWP) and to maximise the efficiency of dairy production systems. Finding a balance between improving productivity and suppressing the range and quantity of GHG produced in dairy production is crucial in order to maintain sustainability in the future. The Langhill herd is part of a long term genetic x feeding systems study, representative of a range of dairy production systems which may be found in the UK. Two feeding regimes (low forage (LF) and high forage (HF)) were applied to each of two genetic lines (control (C) and select (S) genetic merit for milk fat plus protein) giving four contrasting dairy production systems (LFC, LFS, HFC, HFS). Biological efficiency (production and energetic) and environmental efficiency (GWP) were assessed by way of life cycle analysis (LCA), accounting for dairy system inputs and outputs from off-farm production of imported feeds and fertilisers to raw milk leaving the farm gate over a period of seven years. Calculations were conducted using the Intergovernmental Panel on Climate Change (IPCC) methods, with system specific data implemented where possible.

Select genetic line under low forage regime (LFS) had the highest gross production and energetic efficiencies ( $p < 0.001$ ). In LFS, milk yields were 56% higher per cow than the lowest ranked HFC system, representing a difference of around 3500kg per cow. Milk solids yield per kg dry matter intake was 18% higher in LFS compared to HFC. High forage with control genetic line required 17% more net energy intake than LFS to produce each kg of milk solids. LFS allocated the highest proportion of net energy to lactating after accounting for body maintenance ( $p < 0.001$ ). Rate of change in efficiency throughout lactation varied significantly ( $p < 0.001$ ) amongst systems, with loss of efficiency minimised in LFS and greatest in HFC. However, LFS involuntary culling rate was significantly higher than other systems ( $p < 0.001$ ).

LFS was the most environmentally efficient system and HFC the least ( $p < 0.001$ ), both per unit productivity and per unit total land use. Implementing low forage regime with select genetic line lowered GWP per kg energy corrected milk (ECM) by 24% compared to HFC ( $p < 0.001$ ). GWP of LFC was around 8% lower per kg ECM than HFS ( $p < 0.001$ ). Methane from enteric fermentation contributed the greatest proportion of overall GWP (46-49%) in all systems. However, key factors in the differences amongst systems were higher off-farm CO<sub>2</sub> equivalent emissions under low forage, and higher on-farm N<sub>2</sub>O emissions under high forage regime. HFC produced 91% more nitrous oxide per kg ECM from animal manures compared to LFS, and 65% more N<sub>2</sub>O from applied manufactured fertilisers ( $p < 0.001$ ). Conversely GWP associated with off-farm production of imported feeds in LFS was 11% higher than in HFC ( $p < 0.001$ ). In low forage systems high gross emissions were offset by high productivity but this was not the case for the high forage systems.

Cows of high genetic merit managed under a Low Forage feeding regime had improved production, energetic and environmental efficiencies. However, issues with animal health and fertility raise questions about long term sustainability of the LFS dairy production system, emphasising the importance of examining trade offs between systems.

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## **Chapter One**

## **Chapter One**

### **General Introduction**

#### **1.1 Global Climate Change**

The Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) stated that warming of the climate system is unequivocal, and that most of the observed increase in global average temperatures since the mid-20th century is very likely due to an observed increase in anthropogenic greenhouse gas (GHG) concentrations (IPCC, 2007a). Emissions of GHG have been escalating since the Industrial Revolution, and the atmospheric concentration of carbon dioxide CO<sub>2</sub> has risen to its highest level in at least 800,000 years (Luthi et al., 2008). If unchecked, future climate implications of this rise include further increases in mean annual temperature and a reduction in mean precipitation. At the present rate, the IPCC project a global mean temperature rise of 0.2°C for each of the next two decades. In the longer term, projections range between a 2°C and 4°C rise by 2100 compared to the end of the 20<sup>th</sup> century, depending on global GHG emissions scenarios (IPCC, 2007a).

It is also projected that there will be an associated increasing likelihood of extreme weather events around the world. In Europe this will enhance, for example, the occurrence of heat waves, the intensity of daily precipitation events and frequency of storm surges (IPCC, 2012). In turn the social and economic consequences of climate change will be felt across the globe, with a predicted decline in soil and water quality, increased incidence of drought, and new vectors for the spread of pathogens impacting upon agriculture and aquaculture (IPCC, 2007c). Low lying coastal zones face the threat of global sea level rise, owing to melting of polar icecaps and thermal expansion of the oceans. The recent Living Planet Report stated that if GHG emissions continue at or above current rates, the natural resilience and natural adaptability of many ecosystems is likely to be exceeded (WWF, 2012), with far reaching consequences for global biodiversity.

### 1.1.1 Global Warming Potential

Greenhouse gases are so-called owing to their ability to trap radiant energy from the sun in the atmosphere and alter the Earth's average near-surface air temperature. Principle GHG emitted globally include CO<sub>2</sub>, methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). Since the beginning of industrialisation around 1750, atmospheric concentration of CO<sub>2</sub> has increased from around 280 parts-per-million (ppm) to around 379ppm, with over half of that increase arising since 1970 (IPCC, 2007b). Atmospheric CH<sub>4</sub> has increased from 715 to 1774 parts-per-billion (ppb) and N<sub>2</sub>O from 270 to 319 ppb over the same period. These different GHG vary in their capacity to reflect or trap energy in the atmosphere, referred to as their global warming potential (GWP). Compared over a standardised 100 year period and expressed in units of kilograms of CO<sub>2</sub> equivalent (kg CO<sub>2</sub>e), the GWP of CH<sub>4</sub> and N<sub>2</sub>O are estimated to be 25 and 298 times greater respectively than that of CO<sub>2</sub> (IPCC, 2006). Thus, when considering the relative GWP of these contributing GHG, even a small reduction in the amount of CH<sub>4</sub> and N<sub>2</sub>O emitted may lead to a substantial reduction in overall GWP.

### 1.1.2 Policy and legislation

Under the terms of the 1996 Kyoto Protocol, industrialised countries entered a legally binding commitment to report and reduce their GHG emissions. The commitment period of the original treaty expired in December 2012, and an amendment was made at the 2012 United Nations Climate Change Conference to accommodate an extension period to 2020 while a new treaty is developed (United Nations, 2013). The Kyoto protocol committed European Union member states to a reduction in GHG emissions of 8% compared to 1990 baseline levels by 2012, and 20% by 2020. However, many nations including the UK have individually implemented strategies to combat emissions at a higher level. At present Scotland contributes around 48 Mt CO<sub>2</sub>e in GHG emissions annually, representing a reduction of around 31% relative to 1990 baseline levels having already been achieved (Thomas et al., 2011). In 2009 the Climate Change (Scotland) Bill was passed,



committing to a reduction in GHG emissions of 80% by 2050 with an interim target of 42% by 2020 (Scottish Government, 2009a). These ambitious targets ensure that Scotland is placed at the forefront of global efforts to tackle climate change.

## 1.2 Agriculture and Climate Change

### 1.2.1 Contribution of agriculture and dairy production

Approximately 18% of the world's total GHG emissions are associated with livestock production (Gerber et al., 2010), representing a share greater than that of transport. Global livestock production is projected to double between 2010 and 2050 (Steinfeld et al., 2006) meaning that the environmental impacts of this sector must be cut in half simply to avoid increasing levels beyond the present. This presents the challenge of meeting society's increasing demand for products such as meat and dairy, while at the same time meeting global commitments to decrease GHG emissions. Dairy production is an important contributor of GHG within the agricultural sector, with emissions arising from processes both on and off the farm (Weiske et al., 2006). A study by the Food and Agriculture Organization of the United Nations (FAO) defined the contribution of dairy production systems to be 2.7% globally, with an additional 1.3% attributed to its associated beef output (Gerber et al., 2010). The agricultural industry contributes approximately 16% of Scotland's GHG emissions (Thomas et al., 2011), making it the third largest contributor of GHG nationally after the energy (38%) and transport (22%) sectors. Further, Thomas et al. (2011) note that agriculture is responsible for around 85% of N<sub>2</sub>O emissions nationwide.

### 1.2.2 Greenhouse gas emissions from dairy production systems

National inventory records report dairy production systems as contributing 18% of the total Scottish agricultural sector emissions, and 2.0-2.5% of the total overall GWP in the national inventory (DairyUK, 2009; Sheane et al., 2011). These

inventory figures do not, however, include the associated emissions from off-farm processes, while emissions such as fuel use are reported under the national inventory for energy (DairyCo, 2012a). Therefore in reality the overall contribution of dairy production systems to national GHG emissions is likely to be higher.

The ratio of GHG emitted from dairy production systems differs significantly from that observed in non-agricultural industry sectors (Flysjö et al., 2011) in that CO<sub>2</sub> is not the dominant emission. Methane is produced as a by-product from microbial breakdown of carbohydrates in the digestive tracts of ruminants. This process, called enteric fermentation, is influenced by the animal's production level, feed composition and the type of feed consumed (Cederberg and Flysjö, 2004; Chagunda et al., 2009; Garnsworthy et al., 2012). Methane also arises on-farm from the anaerobic bacterial fermentation of animal excreta. Together, enteric fermentation and manure represent around 52-65% of the total GWP of conventional dairy production systems (Cederberg and Mattsson, 2000; Haas et al., 2001) and about 30 to 40% of the total anthropogenic methane emissions (Steinfeld et al., 2006). The second greatest contributing GHG from the dairy sector is N<sub>2</sub>O, with emissions comprising around 25-32% of the total GWP of conventional dairy production systems (Cederberg and Mattsson, 2000; Haas et al., 2001; Saunders and Barber, 2009). Direct N<sub>2</sub>O emissions result from deposition of manure and urine on pasture, the storage of farm manure and slurry, the application of manure and chemical fertilisers to crops and from decomposition of crop residues in the soil (Gerber et al., 2010). Furthermore, N<sub>2</sub>O emissions arise indirectly from the volatilisation and subsequent re-deposition of ammonia from applied fertilisers and animal manures, and as a result of leaching and runoff from agricultural soils (IPCC, 2007a). Carbon dioxide results mainly from energy use and the combustion of fossil fuels on the farm and in the processes surrounding external production and transport of animal feeds and manufactured fertilisers. The dynamic relationship between the working and natural processes of a dairy production system leads these three GHG to be inexorably linked. Thus, when considering their relative GWP, even a small shift in the balance of these GHG emissions produced may lead to a substantial difference in overall GWP.

The average GWP of dairy production in the UK was recently estimated in a national study to be 1.3 kg CO<sub>2</sub>e per litre of milk produced (DairyCo, 2012a). This figure incorporated farms of all different types of dairy production system, varying in size, animal breed and management practice, and the GWP ranged from 0.8 to 2.8 kg CO<sub>2</sub>e across the study. The FAO estimate for global GWP from milk production, is considerably higher at 2.4 kg CO<sub>2</sub>e per unit milk (Gerber et al., 2010), obtained employing similar but less detailed methods. This includes a range from 1.3 kg CO<sub>2</sub>e in developed countries such as those in North America and Europe, to approximately 7.5kg CO<sub>2</sub>e in developing regions such as sub-Saharan Africa. Although dairy production in the UK ranks amongst the most efficient globally with respect to climate change impacts, there are still opportunities to make important reductions in the GWP. The Scottish Climate Change Delivery Plan (Scottish Government, 2009b) set the agricultural sector a target to reduce emissions by 1.3 Mt CO<sub>2</sub>e by 2020. Although the dairy industry was not charged with a specific individual target under the plan, any potential improvements made in the GWP of dairy production systems will make a substantial contribution towards attaining the government's ambitious climate change goals. The high level of emissions in the dairy production industry also opens up opportunities for mitigation actions.

### 1.2.3 Mitigation options

The greatest impact on reducing farm emissions at national level could be achieved by decreasing the country's current production levels of meat and dairy products, or more simply, reducing the number of animals. However, this would be potentially self defeating. By imposing a limit on domestic production, retailers would have to source imported produce to satisfy demand, leading to potentially even higher GHG emissions per unit of product. Therefore, if the dairy industry is to continue to meet demand for dairy products, ways to minimise GHG emissions per unit product in a sustainable way will become increasingly important.

Steinfeld et al. (2006) stated that increasing the efficiency of livestock production through animal breeding and nutrition are the most promising ways to reduce GHG

emissions. It has been demonstrated that improvement in traits such as milk yield and daily feed intake of dairy cows are heritable through genetic selection (Veerkamp et al., 1995). It has also been shown that high yielding dairy cows with high feed intakes are associated with a lower enteric CH<sub>4</sub> output per unit milk (Garnsworthy, 2004; Bell et al., 2010), therefore herd numbers may be optimised for level of production. Casey and Holden (2005a) stated that a move towards production systems with fewer cows producing more milk at lower stocking rates was required to reduce overall GWP. Selective breeding in dairy cows leads not only to higher milk production, but through increased efficiency of feed use could result in reduced resource requirements per unit milk. This is important when considering where the components of a cattle feed ration are derived from for a given dairy production system. Purchasing animal feeds from external sources shifts the burden of production off the farm, but the associated environmental costs must still be considered as part of the dairy production system. However, many purchased concentrated feeds available to the dairy industry have been sourced as by-products from the distilling and brewing industries, therefore a substantial part of the environmental costs of this feed production has already been accounted for under a different industry sector.

Recent analysis using marginal abatement cost curves (Moran et al., 2011; Eory et al., 2013) estimated that improvements in dairy cow genetics and animal management, as well as improved farm management practices, represented both real and cost effective GHG mitigation measures. These farm management practices included the management and storage of animal manures, soil management, and the timing and efficiency of organic and inorganic fertiliser application. Investigating storage of animal manures, Janzen et al. (1998) found that a liquid slurry system increased emissions of CH<sub>4</sub> owing to the anaerobic conditions of liquid storage. Conversely, this increase in CH<sub>4</sub> was accompanied by a reduction in emissions of N<sub>2</sub>O from the manures which would have been observed from solid dry storage of manure, or from deposition by animals at pasture. Nitrous oxide emissions would still arise, however, from the subsequent application of stored slurry to the land. Therefore from a GHG perspective, the proportion of manure handled under different

management practices amongst dairy production systems holds potential to influence the overall balance of GWP and merits further examination. This is particularly important when considering fully housed management systems, at present accounting for around 5% of UK dairy herds (Wilkinson et al., 2011), where up to 100% of animal manures can be stored as liquid slurry.

There are therefore many potential means by which to mitigate GHG emissions from dairy production systems. However, Weiske et al. (2006) noted that many mitigation measures suggested by previous research studies in the literature do not always result in the expected reduction potential when evaluated at the farm or whole system level. This is due to the trade-offs amongst GHG emissions, where a reduction in GWP of one system component will necessarily influence the GWP of another. For example, Chagunda et al. (2009) showed that although increasing milk production was associated with a reduction in enteric CH<sub>4</sub> per unit milk, excreted nitrogen could increase depending on the genetic merit of animals and the specific details of the production system. It has also been demonstrated that while implementing an organic system can reduce overall emissions of CO<sub>2</sub> and N<sub>2</sub>O, the reduction in GWP may be nullified by lower production and an inherent overall increase in enteric CH<sub>4</sub> (de Boer, 2003). This highlights that studies should thus not examine selected snapshots of a dairy production system, such as enteric CH<sub>4</sub>, in isolation. Rather, studies should always consider associated emissions to ensure that reductions in one part of a system do not stimulate higher emissions elsewhere (de Klein and Eckard, 2006). The overall GHG pollution potential from dairy production systems is, therefore, a dynamic process which should be assessed at a whole systems level in order to optimise the total output of pollutants against productivity. It is this complex balance of the range of processes within the whole dairy farming system that calls for further research.

#### 1.2.4 Greenhouse gas accounting and Life Cycle Assessment

Greenhouse gas accounting, often metaphorically referred to as a carbon footprint, can be broadly considered as the sum of GHG emitted throughout a defined process.

The IPCC (2006) guidelines for national greenhouse gas inventories state that accounting procedure should adopt one of three hierarchical tiers of methods that range from default emission factors and simple equations to the use of local-specific data and models to accommodate explicit circumstances. Tier 1 method is the simplest level of GHG accounting, where calculations are, for example, based on multiplying the number of cattle present by an emission factor. At Tier 1 level these emissions factors are generic internationally-applied default values. A more detailed method is employed at Tier 2 level, where emissions factors are country- or region-specific, and appropriate for predominant land use, livestock categories and climatic conditions. Finally, Tier 3 represents the highest level of reporting, requiring comprehensive and system-specific data. Internationally approved equations and emissions factors at Tier 1 and 2 levels are provided by the IPCC (2006). The reporting of GHG emissions from agriculture has in the past been relatively simplistic, employing Tier 1 methods (DairyCo 2012a). However, this method necessitates that no differences can be discerned amongst different production systems or individual farm management practices. In order to achieve a better representation of the reality of GHG emissions from agricultural systems, either a Tier 2 or a Tier 3 approach is essential.

A product based carbon footprint, such as for dairy production, is also usually based upon a Life Cycle Assessment (LCA) method (IDF, 2010). Life Cycle Assessment stands today as the pre-eminent tool for estimating environmental effects caused by products and their processes (Reap et al., 2008), favoured for being very adaptable and for its capability in accounting for all aspects of a process from the ‘cradle to the grave’. The LCA thus enables calculation of not only GHG, but further impact categories such as land use, eutrophication and ecotoxicity (Reap et al., 2008). The LCA process is described by the international standard ISO:14040 framework (ISO, 2006), and defines how the LCA progression is divided into four distinct phases: goal and scope definition, inventory analysis, impact assessment and finally interpretation. Further methodological guidelines for GHG accounting exist for the UK in the British Standards Institute (BSI) PAS:2050 (BSI, 2011). Audsley et al. (1997) investigated the application of LCA to agriculture, identifying methodological

difficulties of the process and harmonising the various approaches employed for the industry. While the ability to define boundaries for a given system is favourable for the environmental assessment of agriculture, the impact categories and functional unit of the classical LCA model must be adapted to the specific agricultural production process (Haas et al., 2000). However, Reap et al. (2008) noted that this adaptation can give rise to problems through studies' potential localised techniques and boundary selections, as well as in the definition of a functional unit. The life cycle of dairy production systems is often further complicated by the production of co-products (meat, manure) created in addition to the main product (milk). To this end the International Dairy Federation developed a standardised sector-specific guideline to GHG accounting and allocating for the dairy industry (IDF, 2010).

#### 1.2.5 Studies at production systems level

Over the past decade, studies have been undertaken at production system level examining the relationships between GHG in dairy farms. Many studies have been aimed towards demonstrating the application of GHG accounting methods such as LCA in dairy farming (Hospido et al., 2003; Thomassen and de Boer, 2005; O'Brien et al., 2011). Other studies assessing whole farm systems have been conducted mainly in the context of providing a comparison between the environmental efficiency of conventional and organic systems (Cederberg and Mattsson, 2000; Haas et al., 2001; de Boer, 2003; Thomassen et al., 2008b). Furthermore, many studies have served to inform their respective national inventories or to examine the differences between typical systems at a national level (Cederberg and Flysjö, 2004; Basset-Mens et al., 2005; Casey and Holden, 2005a; Saunders and Barber, 2007). For example, in a comparison of high- and low-input systems in New Zealand, Basset-Mens et al. (2009b) found that a high-forage, low-input system had 10%-20% lower GWP and associated energy use between 50% and 70% lower than the high input systems. In the UK, Williams et al. (2006) used national data to model and compare the environmental impacts of alternative methods of dairy production, such as increasing milk yield of the national herd and reducing Autumn calving numbers. However, rather than summarising the GWP of dairy production systems at a

regional or national level, there is need for studies which will examine in depth the potential for variation in GWP amongst different conventional dairy systems within the same geographic region. In the literature, questions have also been noted over the robustness of drawing direct comparisons between the results of different systems-level dairy studies (Basset-Mens, 2008; Yan et al., 2011). This is due to, for example, differences in studies' level of detail, definition of system boundaries, emissions factors and allocation techniques. There is therefore a need to conduct analysis where estimated GWP of different dairy production systems are truly directly comparable. Such an analysis could also incorporate the effect of improving the genetic merit of the dairy herd while implementing different feed and management systems. If the dairy production industry is to make real reductions in its GWP and contribute to achieving government climate change targets, there is a pressing need to identify a dairy production system which would make the lowest contribution to climate change impacts.

#### 1.2.6 Functional units

The functional unit (FU) describes the primary function of a product system, and provides a clearly defines and measurable reference to which the input and output data from different systems are normalised (ISO, 2006). In dairy research studies, this has most often been defined as the mass of energy corrected milk (ECM) leaving the farm gate (de Boer, 2003). Energy corrected milk is a correction factor used by the dairy industry which considers both the fat and protein content of the milk (Cederberg and Mattson, 2000), and is thus intended to allow direct comparison between data from different systems. However, in a review paper evaluating LCA of European milk production, Yan et al., (2011) noted the employment of ten different FU across different studies. As environmental pollution, and climate change in particular, is a global issue, it is often preferable to express GWP referenced in terms of land use, including land both on and off the farm. For studies which intend to inform national inventory reporting, it is also necessary to choose a FU coupled with land area (IPCC, 2006). Furthermore, some studies choose to express results with a FU suitable for economic calculations, for example in terms of milk solids (milk fat



plus protein content) (O'Brien et al., 2012) or processed packaged milk ready for delivery (Hospido et al., 2003). With the potential for a lack of consistency amongst accounting methods at present, there is a need to be sure that the results from LCA in the present study can be comparable in a wider context. A few LCA of dairy production systems studies have employed multiple FU in the same analysis (Haas et al., 2001; van der Werf et al., 2009; O'Brien et al., 2012). The results of those studies suggest that the perceived relative environmental efficiency of dairy production systems could change based on which FU was employed to present the results. However, there has not so far been a study directly investigating the effect of different FU chosen on the relative environmental efficiency of comparable dairy production systems.

### 1.3 Production efficiency of livestock

Agricultural practices have changed significantly over the last century, as the intensification of agriculture increased production and efficiency to satisfy greater demand for animal products at low cost (Steinfeld et al., 2006). Advances in efficiency of dairy production have made possible as a result of changes in breeding, nutrition and management practices (Capper et al., 2009). Improvements to the dairy cow's environment and health have also been shown to improve milk production (Bell et al., 2008). Wilkinson et al. (2011) stated that milk yields in UK pasture-based systems are restricted to, on average, four to five thousand litres per cow. Mixed housing/grazing systems average six to eight thousand litres, while in continuously housed systems milk yields can rise to average twelve thousand litres per cow (Wilkinson et al., 2011). With the current additional pressure of minimising the environmental impacts of dairy production systems, increasing productivity through management and genetic selection is of further significance. It is noted, however, that genetic selection focussed on increasing milk yields has been to the detriment of wider health and fertility traits (Miglior et al., 2005). Studies have shown that selection for production alone has predisposed cows to utilise body energy reserves to support lactation which are not fully replaced (Pollott and Coffey, 2008). In turn, this predisposition is unfavourably associated with cows'

reproductive performance, health and mastitis (Pryce et al., 1999; Veerkamp et al., 2001; Heringstad et al., 2003). Therefore, in order to investigate the future sustainability and environmental efficiency of dairy production systems, studies must first consider the systems' efficiency of production in conjunction with traits indicating animal performance.

Gross production efficiency is often measured as simply the cows' milk yield or milk solids per unit feed intake, or per unit bodyweight. Studies have also investigated cows' feed conversion efficiency throughout lactation (Veerkamp and Emmans, 1995; Coleman et al., 2010), and investigated efficiency in terms of cows' energy balance (Veerkamp et al., 1994; Coffey et al., 2004). Prendiville et al. (2011) reported the variation observed between different breeds of dairy cows in terms of their production and energetic efficiency profiles throughout lactation. However, studies have not so far examined in depth the potential for variation in production efficiency within a breed maintained under different management systems within a conventional farm.

## 1.4 The thesis

### 1.4.1 Aim of the study

Due to the high level of GHG emissions from dairy industry, it is important to investigate ways to maximise the efficiency of dairy production systems and at the same time to minimise their GWP. This project aimed to investigate the relationship between dairy farming processes, the productivity of dairy systems and their associated environmental pollutants, through the implementation of Life Cycle Analysis. In order to consider the long term viability of dairy production systems, this project aimed to investigate both their biological efficiency and environmental efficiency. Climate change mitigation measures to be considered in this project were improving the genetic composition of the dairy herd, combined with different feed and management systems. Finding a balance between improving productivity and

suppressing the range and quantity of GHG produced in dairy production is crucial in order to maintain sustainability in the future. In so doing, the study intended to not only advance the work in this field, but also draw from and expand upon existing work conducted by Scotland's Rural College (SRUC) on feed intake, emissions, system modelling, animal performance and health. Ultimately this project aimed to contribute to identifying a sustainable dairy production system which may be optimised for both productivity and GWP.

#### 1.4.2 Data source

This research was based on the established long-term Holstein-Friesian genetic line and management systems project, situated at SRUC Dairy Research Centre, Crichton Royal Farm, Dumfries. Also known as the “Langhill” herd, the project is one of the longest running genotype  $\times$  environment experiments in the world. From 1974 the experiment was based at Langhill Farm outside Edinburgh before moving to the present location in 2002, and its structure is briefly summarised here.

Farm-derived data used for this present study were collected over the period January 2004 to December 2010, and incorporated specific details of four distinct systems within a conventional farm. Animals were maintained in two feeding groups - high forage (HF) and low forage (LF). The HF systems aimed to provide a target of 75% by dry matter of the herd's mixed ration diet when housed from home grown crops, and 25% of ration composition coming from purchased concentrated feeds. Cows in the HF systems were turned out to graze ryegrass pasture when available, and therefore the total home grown element of the annual HF diet was actually greater than 75%. In contrast, the LF systems were fully housed; the herd retained indoors all year round and fed a diet of approximately 45% home grown forages, with 55% of diet from purchased concentrates imported onto the farm. Within each forage system, animals comprised two contrasting genetic lines. Control (C) animals were bred to be of average UK genetic merit for milk fat and protein production, and Select (S) animals represented the top 5% of UK genetic merit. Maintaining the

specific details of these groups in a long term genotype x feeding regime project resulted in four divergent dairy production systems – HFC, HFS, LFC and LFS. These production systems were representative of the interaction between forage regime and genetic line, and form the basis of all analyses presented in this thesis.

Further data were sourced where required from relevant authorities in the literature. These included data, equations and coefficients employed in, for example, calculation of cows' net energy requirements (NRC, 2001), and in calculation of GHG emissions (IPCC, 2006; Carbon Trust, 2010b; DEFRA, 2011a). Data on grazing intake of cows were sourced from a previous study of the Langhill herd (Bell et al., 2010).

#### 1.4.3 Objectives

The objectives of this thesis were:

- a. To determine the animal performance and biological efficiency of four divergent dairy systems.
- b. To determine the global warming potential of four divergent dairy systems.
- c. To determine the effect of uncertainty in emissions factors and farm-derived data on the estimated global warming potential
- d. To determine the effect of changing the functional unit on the results from environmental impact assessment in the different systems.

#### 1.4.4 Summary of analysis for chapters

##### *Chapter 2: Animal performance and biological efficiency of four dairy production systems*

Before investigating the environmental efficiency, this chapter considered the biological efficiency as an indicator of the long term viability/sustainability of the dairy systems. Analysis in chapter 2 began by examining the effect of production system on differences in performance traits describing lactating Holstein-Friesian

cows from four conventional dairy production systems. The four systems comprise two feeding regimes applied to each of two genetic lines, thus the systems were representative of the interaction between forage regime and genetic line. In addition, the chapter aimed to investigate the effect of production system on the gross production efficiency and net energetic efficiency of dairy systems throughout lactation. Key energetic efficiency measures were to be the cows' net energy intake required to produce one kg of milk solids, and the proportion of net energy allocated to lactation after accounting for maintenance. Further, the analysis intended to examine the rate of change in systems' energetic efficiencies, throughout a lactation period. These assessments aspired to provide a comparison of the biological efficiency and long term viability of the four dairy production systems. Establishing a measure of the animal performance and biological efficiency of the dairy production systems was anticipated to serve as a platform to build on for subsequent analysis of environmental impacts.

### *Chapter 3: The effect of dairy production system on the balance of global warming potential in a conventional dairy farm*

It was noted earlier that improved animal genetics, feeding and farm management practices were all promising and cost effective mitigation measures for reducing GHG emissions from dairy production systems. Through the application of LCA, the purpose of this chapter was to analyse the effect of dairy production system on the overall GWP per unit milk produced. The four systems were located within the boundaries of the same conventional dairy farm, therefore enabling direct comparison of a range of representative systems possible in the UK. Employing LCA permits observation of exactly where hot-spots occur in the balance of processes contributing GHG emissions amongst systems. Impact assessment was to be conducted using IPCC Tier 2 methods, with the analysis implementing system-specific values where possible in order to properly define differences amongst systems. The trade-off between emissions and milk yield was anticipated to vary significantly amongst the four systems. Analysis in this chapter aimed to consider the magnitude of the effects observed on GWP by implementing the feed and

management system, the genetic improvement to the herd, and the interaction between them. In addition, any significant differences amongst system traits determined in chapter 2 were required to be considered alongside the environmental impacts. Any potential loss of productivity associated with poor animal health or reduced biological efficiency may have counter-balanced initial gains in GWP made through implementing a particular production system. Furthermore, this chapter intended to examine the influence of uncertainty in farm-derived data and IPCC emissions factors on the estimated GWP of the dairy production systems by performing sensitivity analysis. This was anticipated to provide a robust comparison of the environmental efficiency of four dairy production systems with respect to GHG, enabling the optimal system to be identified. The results from LCA were then intended to provide a platform from which to conduct further analysis in chapter 4.

#### *Chapter 4: The effect of functional units on the environmental efficiency of dairy production systems*

This chapter aimed to examine the effect of employing different functional units on the relative environmental efficiency of four dairy production systems. Building on the LCA impact assessment conducted in chapter 3, the GWP of four dairy production systems were to be referenced to five selected FU previously employed by LCA studies in the literature. This phase of the study was proposed to examine whether trends across the four systems were observed equally when using a different FU. Furthermore this chapter intended to assess the merit and suitability of each functional unit, examining the reasons underlying their effect on the relative efficiency of the four directly comparable systems. Analysis for this chapter also introduced a proposed original ‘dual’ FU which incorporates both the productivity and land requirements of a dairy production system. It was suggested that such a unit could thus reflect improvements made in the biological efficiency of animal production and efficiency of either crop production or land-use.

This chapter ultimately aimed to assess whether conclusions drawn about the environmental efficiency of a dairy production system depended on the measure used, and to settle debate on the most appropriate measure to employ for future work.

### *Chapter 5: General Discussion*

These three analyses were then to be brought together in the general discussion chapter. General discussion was to focus on the future viability and sustainability of the four dairy production systems under investigation. Findings from investigating the systems' performance traits, biological efficiency (production and energetic) and environmental efficiency were drawn together along with a consideration of how perceived efficiency of the dairy production systems is influenced by the methods and functional units applied. This chapter aimed to consider whether the identified 'optimal' system would in fact be a sustainable option for dairy production in the future. What levels of environmental gains might be anticipated if the dairy industry were to adopt the leading system? To what extent would this help meet government climate change targets, and could aspects of this system be easily implemented to augment existing dairy production systems without need for a radical overhaul? General discussion also intended to consider the possible future sustainability of the four dairy production systems, and whether these types of dairy systems could be adopted widely at national level.

## **Chapter Two**



## **Chapter Two**

### **Animal performance and biological efficiency of four dairy production systems**

#### **2.1 Introduction**

Modern livestock systems are confronted by the challenge of increasing global demand for products such as meat and dairy produce, while at the same time reducing their environmental impact. Traditionally, increased milk production has been achieved through higher stocking rates or higher productivity per cow (Dillon et al., 1995). These changes necessitate an increase in animal feed requirements, therefore coupled with increased forage cropping, pasture and imported feeds, along with associated labour and production costs. Feed costs can account for around 80% of total variable costs of milk production (Shalloo et al., 2004), therefore the efficiency of converting feed into additional volumes of milk is of considerable importance (Coleman, 2010). With the current focus on efficient use of resources and the additional pressure of minimising the environmental impacts of dairy systems, increasing productivity through better nutrition and genetic selection is of further significance.

For many years most genetic selection indices worldwide have focussed on increasing milk production, to the detriment of wider health and fertility traits (Miglior et al., 2005). Heringstad et al. (2003), for example, showed that genetic selection for production alone is unfavourably associated with udder health and mastitis, while other studies have similarly indicated a negative association with reproductive performance (Pryce et al., 1999; Veerkamp et al., 2001). Any unfavourable association with health and fertility traits can lead to high involuntary culling rates, potentially undermining gains achieved in productivity. Pryce et al. (1999) noted the importance of examining genotype by environment interactions and the need to account for their effects on animal performance and fertility traits. Coffey et al. (2004) examined the effects of genotype and diet on various cow performance traits, such as milk yield, weight, feed intake and body condition. These studies found that cows selected for maximum production lost more weight and body energy

over three lactations. This indicates that successive selections for high milk yields have predisposed cows to utilise body energy reserves to support lactation which are not then fully replaced, in turn leading to fertility and health problems (Pollott and Coffey, 2008). This observation is particularly important when considering higher genetic merit cows being managed on a pasture or lower quality forage diet.

Examining the biological efficiency (production efficiency and energetic efficiency) of cows' performance throughout lactation, together with animal traits, provides a measure of the sustainability of dairy production systems. There are a multitude of ways to define the feed efficiency or production efficiency of dairy production systems. Milk yield per unit of dry matter consumed is one measure of gross production efficiency (Britt et al. 2003). However, this feed conversion method does not account for mobilization of body tissue for production. Consequently animals losing body condition may appear more efficient (Coleman et al., 2010). Dairy production efficiency has also commonly been measured as daily milk yield or daily milk solids per unit cow body weight (Prendiville et al., 2009; Coleman et al., 2010). Furthermore, the efficiency can be estimated as a measure of the cows' gross, net or metabolisable energy intake (Veerkamp et al 1994; Yan et al., 1997; Prendiville et al., 2009; Xue et al., 2011), or as a measure of their energy balance (Coffey et al., 2004). Measures of feed conversion efficiency, such as residual feed intake (RFI) have also been employed as means of assessing dairy production systems efficiency throughout lactation (Veerkamp and Emmans, 1995; Coleman et al., 2010). Residual feed intake accounts for the difference between animals' observed feed intake and that predicted from their lactational performance, metabolic live weight and live weight change (Veerkamp et al., 1995). Prendiville et al. (2011) reported the variation between different breeds of dairy cows in terms of their production and energetic efficiency profiles throughout lactation. However, studies have not so far examined in depth the potential for variation within a breed maintained under different management systems within a conventional farm. All of these measures of efficiency, however, are unable to account for any fertility issues of dairy cows. Assessment of the production systems' sustainability should therefore consider reproductive performance traits in conjunction with the estimated biological efficiency.

The first aim of this chapter is to examine the effect of production system on differences in production performance and reproductive performance traits describing lactating Holstein-Friesian cows from four conventional dairy production systems. The four systems comprise two feeding regimes applied to each of two genetic lines, thus the systems are representative of the interaction between forage regime and genetic line. The second aim is to investigate the effect of production system on the gross production efficiency and energetic efficiency of dairy systems throughout lactation. Further, the analysis will examine the rate of change in systems' production and energetic efficiencies, quantifying the loss in efficiency over a lactation period. These assessments will provide a comparison of the biological efficiency and, combined with health and reproductive traits, an assessment of the long term sustainability of the four dairy production systems.

## 2.2 Materials and Methods

### 2.2.1 Description of dairy production systems

The study was based on data from Scotland's Rural College's (SRUC, formerly SAC) long-term Holstein-Friesian genetic and management systems project, situated at SRUC Dairy Research Centre, Crichton Royal Farm, Dumfries. Data used were from a period of seven years, from January 2004 to December 2010, and incorporated specific details of the four distinct dairy production systems within a conventional farm.

#### 2.2.1.1 *Feeding regimes*

Animals were maintained in two feeding and management regimes: high forage (HF), which was winter housed; and low forage (LF) which was fully housed. During the housed periods, lactating cows were fed a total mixed ration (TMR) comprising three homegrown forages (ryegrass silage, wholecrop wheat alkalage, wholecrop maize silage) and a purchased feed blend of concentrates. Wheat alkalage is an alkaline preserved wholecrop forage made from mature wheat crop, ensuring high dry matter content and high digestibility. A breakdown of the daily TMR formulation for both feeding regimes is presented in Table 2.1.

**Table 2.1: Total Mixed Ration (TMR) components expressed as percentages of the total formulation offered to lactating cows under High forage (HF) and Low forage (LF)**

TMR Component	Feeding regime	
	High Forage %	Low Forage %
Ryegrass Silage	27.0	45.0
Wholecrop Wheat Alkalage	9.0	15.0
Wholecrop Maize	9.0	15.0
Purchased Concentrate/Blend	53.9	24.2
Minerals	1.1	0.8

The HF feeding regime aimed to provide a target of almost 75% by dry matter (DM) of the herd's TMR diet from homegrown forage, with the remainder of the ration coming from a purchased blend containing rapeseed meal, wheat and barley distillers grains. In addition, cows in the HF group grazed ryegrass pasture when available in summer. In contrast, the LF systems were fully housed all year round and fed a TMR comprising approximately 45% by DM of home grown forages, with 55% from concentrates. Purchased LF blend contained wheat, distillers grains, sugarbeet pulp molasses, soya meal and minerals (Chagunda et al., 2009). Mixed feed rations offered to all groups when housed were formulated from the same conserved forages, and only one ration was offered within each system, irrespective of milking cows' age, parity or stage of lactation. Characteristics of the two rations, including DM content, crude protein (CP), metabolisable energy (ME) and digestibility, are presented in Table 2.2. Lactating cows also received a supplemental 0.25 kg of concentrates each in the milking parlour at every milking session, equivalent to approximately 3% of the daily DM intake from the TMR.

**Table 2.2: Nutritional characteristics of formulated total mixed rations (TMR) for the Langhill herd**

Characteristic	units	High Forage		Low Forage	
		mean	sd	mean	sd
Dry Matter content	g kg <sup>-1</sup>	349	43.7	426	47.8
Crude Protein content	g kgDM <sup>-1</sup>	171	12.2	180	13.5
Digestibility (NCGD)	g kgDM <sup>-1</sup>	757	34.9	852	34.4
Metabolisable Energy	MJ kgDM <sup>-1</sup>	10.8	0.65	11.7	0.44

Descriptive statistics for feed characteristics obtained from analysis of feed sampled weekly over the full study period (SRUC Analytical Services Department). Where: NCGD = neutral cellulase gammanase digestibility, an enzyme based technique used to estimate the digestibility of feed.

#### *2.2.1.2 Genetic lines*

Within each forage regime, animals comprised two contrasting genetic lines. Control (C) animals were bred to be of average UK genetic merit for milk fat and protein production, and Select (S) animals represented the top 5% of UK genetic merit. The Select group cows were sired by bulls with high predicted transmitting abilities for fat plus protein yield, whereas the Control cows were sired by bulls of UK average merit for fat plus protein (Pryce et al., 1999).

#### *2.2.1.3 Dairy Production Systems*

Maintaining the specific details of these groups in the long term genotype x feeding regime project resulted in four divergent dairy production systems – HFC, HFS, LFC and LFS. These systems enabled the effects of diet and genetic merit to be examined, and are representative of the interaction between forage regime and genetic line. The four systems under study also offer a representative cross-section of existing and potential dairy production systems in the UK.

#### *2.2.1.4 Management of dairy production systems*

Animals were managed in the four production systems for three lactations, with year round calving, and herd numbers maintained at approximately 50 cows in each system. Livestock were not permitted to change production systems. Therefore, upon entering their first lactation, cows remained in that system for the rest of their life in the study. Cows were milked three times daily, received equal treatment regarding health and fertility and were under responsibility of the same herdsman. Heifers and cows were serviced by artificial insemination (AI) and were permitted up to a maximum of seven services in order to attain a positive diagnosis of pregnancy (PD+), thereafter being moved out of the study at the end of lactation. Select and Control cows were managed together and groups retained in the same building when housed.

Milk yields were recorded for individual cows after every milking session. Milk fat and protein content were recorded from samples collected from each cow, three times daily, and all cows were sampled on the same day each week. Liveweights were recorded daily for cows after every milking session. Daily TMR intake of

individual lactating cows was recorded 3 days out of every 6 using automated HOKO feeding gates (Insentec BV, Marknesse, The Netherlands), with animals feeding from behind a strap on the alternate 3 days. Samples of all forages and rations were collected weekly and sent to SRUC Analytical Services Department, Bush Estate, Penicuik. Laboratory analysis included the DM content of samples, metabolisable energy (ME) content, crude protein (CP) content and digestibility of feeds.

### 2.2.2 Data

Covering the study period 149,829 validated daily records, comprising a record of daily milk yield and animal liveweight, were sourced from 615 lactating cows. Daily records comprised; 43,792, 39,542, 35,246, and 31,249 data for the systems LFC, LFS, HFC and HFS respectively, and; 65,016, 48,154 and 36,659 records for parities 1, 2 and 3 respectively. A total of 119,594 validated feeding records for daily dry matter intake (DMI) were sourced, comprising; 44,334 and 40,064 records for LFC and LFS cows, and; 18,608 and 16,588 for HFC and HFS cows. Fewer feed intake records were available for HF as these cows were grazing in the summer. There were 21,156 weekly records for milk fat and protein content, comprising 6,128, 5,606, 4,974 and 4,447 records for LFC, LFS, HFC and HFS respectively. Individual cows' weekly averages for daily milk yield, daily milk solids (fat plus protein), daily DMI and liveweight were used in the analyses of production efficiencies. There were 2,612 recorded services via AI of Langhill heifers and cows, and 389 records of culling from the herd during the period.

### 2.2.3 Performance traits and measuring efficiency

Production traits included were: milk yield (MY), milk fat (F), milk protein (P), animal liveweight (LW), and dry matter intake (DMI). Traits were also selected as indicators of potential fertility problems, including: involuntary culling rate from the herd (INV), calving interval (CI) and the number of services required to attain a positive diagnosis of pregnancy (PD+).

Production efficiencies evaluated were: daily energy corrected milk yield per 100kg of cows' daily liveweight ( $ECM/LW_{100}$ ), milk solids yield per 100kg liveweight

(MS/LW<sub>100</sub>), milk solids yield per unit dry matter intake (MS/DMI) and the total annual energy corrected milk yield (Adj ECM) multiplied by an adjustment factor to account for differences in number of days in milk. The factor applied was obtained by dividing the lactation length by calving interval, giving the proportion of a year in which a cow from a given production system was lactating. Although surplus calves comprise part of the dairy systems' output, production efficiency in this study focussed on the milk component of production. Biological efficiencies considered in terms of net energy (energetic efficiency) were: net energy intake required to produce 1kg milk solids (NE<sub>in</sub>/MS) and the proportion of net energy utilised for milk production after accounting for maintenance (NE<sub>lact</sub>/(NE<sub>in</sub>-NE<sub>m</sub>)).

Energy corrected milk (ECM) is milk yield corrected for its fat and the protein content. Following Sjaunja et al (1990), the equation used in this study was:

**Equation 2.1: Energy corrected milk (ECM) by Sjaunja et al (1990)**

$$\text{ECM (kg)} = 0.25M + 12.2F + 7.7P$$

where M = milk yield (kg), F = fat content (kg), P = protein content (kg)

Net energy intake is a measure of the available energy used by an animal within the body for maintenance and for various forms of productivity, such as milk production, growth and pregnancy (MacDonald et al., 1995). Equations employed in this study to estimate net energy use in dairy cattle are presented in Table 2.3.

**Table 2.3: Equations used to estimate net energy (NE) requirements in dairy cattle**

Variable	Units	Equation
NE <sub>in</sub>	MJ day <sup>-1</sup>	= NE <sub>m</sub> + NE <sub>lact</sub> + NE <sub>a</sub> + NE <sub>g</sub> + NE <sub>p</sub>
NE <sub>m</sub>	MJ day <sup>-1</sup>	= 0.308*LW <sup>0.75</sup>
NE <sub>lact</sub>	MJ day <sup>-1</sup>	= MY*(1.47 + 0.4*F)
NE <sub>a</sub>	MJ day <sup>-1</sup>	= C <sub>a</sub> *NE <sub>m</sub>
NE <sub>g</sub>	MJ day <sup>-1</sup>	= 22.02*((LW/(0.8*MW)) <sup>0.75</sup> )*WG <sup>1.097</sup>
NE <sub>p</sub>	MJ day <sup>-1</sup>	= C <sub>p</sub> *NE <sub>m</sub>

All equations were based on NRC (1996). Where: NE<sub>in</sub> = net energy intake, NE<sub>m</sub> = net energy for maintenance, NE<sub>lact</sub> = net energy for lactation, NE<sub>a</sub> = net energy for activity, NE<sub>g</sub> = net energy for growth, and NE<sub>p</sub> = net energy for pregnancy. LW = cow body liveweight, MY = daily milk yield (kg day<sup>-1</sup>), F = milk fat (%), C<sub>a</sub> = weighted coefficient corresponding to animals feeding situation = 0.17× proportion of time spent at pasture, MW = average body weight of lactating cow (kg), WG = average daily weight gain of cows in the herd (kg day<sup>-1</sup>), C<sub>p</sub> = pregnancy coefficient = 0.1 (dimensionless)

#### 2.2.4 Statistical Analysis

The effects of different dairy production systems upon the chosen animal production traits and efficiency measures were assessed using analysis of variance (ANOVA) employing a general linear model (GLM). The model used was:

$$y_{ij} = \mu + S_i + P_j + (S \times P)_{ij} + Z_{ij} + A_{ij} + M_{ij} + W_{ij} + C_{ij} + \varepsilon_{ij}$$

where  $y_{ij}$  was the animal trait (milk yield, milk fat, milk protein, liveweight, dry matter intake, involuntary culling rate, calving interval, number of services to PD+) or measure of biological efficiency under consideration;  $\mu$  was the overall mean;  $S_i$  was the effect of dairy production system (LFC, LFS, HFC or HFS);  $P_j$  was the fixed effect of parity (1, 2 or 3);  $(S \times P)_{ij}$  was the effect of interaction of production system and parity;  $Z_{ij}$  was the fixed effect of season (winter or summer);  $A_{ij}$  was the random effect of calendar year;  $M_{ij}$  was the random effect of month of calving;  $W_{ij}$  was the random effect of week of lactation;  $C_{ij}$  was the random effect of individual cow identity;  $\varepsilon_{ij}$  was the random error term. Fisher tests were used to assess the level of significance of contributing effects, and differences between dairy production systems were determined conducting pairwise comparisons using the Tukey method. Plots of residuals were checked for each trait under examination, and all data were found to meet necessary assumptions for ANOVA. All statistical analysis was conducted using Minitab 16.

The season variable was defined by the availability of grazing pasture. Thus summer refers to the period when HF groups were at pasture, and winter refers to the period when both HF and LF groups were fully housed. Feed intake data from HOKO gates was not available for HF in summer as cows were out at grass. Thus the season variable could not be included in the model for measures directly dependent on feed intake. Therefore, the models for one animal trait (DMI), one production efficiency measure (MS/DMI) and both measures of biological energy efficiency ( $NE_{in}/MS$  and  $(NE_{lact}/(NE_{in}-NE_m))$ ) did not include the effect of season. Cow identity and week of lactation were added as random variables to allow for covariance between subsequent lactations and periods of lactation of the same animals. Data on the



involuntary culling rate were combined for lactations 1, 2 and 3, owing to the small sample size, thus the effect of parity was removed from the model for the involuntary culling rate.

The effect of production system upon the rate of change in biological energy efficiency ( $NE_{in}/MS$  and  $NE_{lact}/(NE_{in}-NE_m)$ ) throughout lactation was assessed by analysis of covariance (ANCOVA). A term for the interaction of production system and week of lactation was included in the GLM previously described, and least squares means obtained for the efficiency of each production system were regressed against week of lactation. Employing ANCOVA enables the comparison of two or more regression lines to determine a significant difference between them (Neter et al., 2004). In this way the  $y$ -variable (efficiency measure) was compared amongst groups (production systems) while statistically controlling for variation in  $y$  caused by variation in the  $x$ -variable (week of lactation). Slopes of fitted regression lines were compared pairwise with null hypothesis that the slopes were not different to each other.

## 2.3 Results

### 2.3.1 Performance traits

The effect of the interaction between production system and parity was found to contribute the lowest variation of any term in the model for all traits. Therefore the interaction term was removed from the model and the analysis re-run in order to focus on the main effects from the model. Results from ANOVA for performance traits of cows in each system are presented in Table 2.4.

**Table 2.4: Performance traits of lactating Langhill cows presented as least squares means (lsm) with standard errors of the mean (sem).**

Variable	Level	Milk Yield		Fat		Protein		Liveweight		DMI		INV		CI		PD+	
		(kg cow <sup>-1</sup> day <sup>-1</sup> )		(g kg <sup>-1</sup> )		(g kg <sup>-1</sup> )		(kg)		(kg cow <sup>-1</sup> day <sup>-1</sup> )		(% )		(days)		(n)	
		lsm	sem	lsm	sem	lsm	sem	lsm	sem	lsm	sem	lsm	sem	lsm	sem	lsm	sem
System	LFC	29.2 <sup>a</sup>	0.06	35.5 <sup>a</sup>	0.18	31.8 <sup>a</sup>	0.0	607 <sup>a</sup>	0.5	16.9 <sup>a</sup>	0.05	18 <sup>a</sup>	2.2	393 <sup>ab</sup>	7.2	2.7	0.07
	LFS	34.9 <sup>b</sup>	0.06	37.7 <sup>b</sup>	0.18	33.6 <sup>b</sup>	0.09	623 <sup>b</sup>	0.5	19.4 <sup>b</sup>	0.05	31 <sup>b</sup>	2.2	410 <sup>c</sup>	7.4	2.7	0.08
	HFC	22.8 <sup>c</sup>	0.07	38.2 <sup>c</sup>	0.18	32.0 <sup>c</sup>	0.09	574 <sup>c</sup>	0.5	16.6 <sup>c</sup>	0.05	10 <sup>a</sup>	2.2	401 <sup>bc</sup>	7.2	2.7	0.07
	HFS	26.4 <sup>d</sup>	0.06	39.9 <sup>d</sup>	0.19	33.5 <sup>b</sup>	0.10	598 <sup>d</sup>	0.5	18.4 <sup>d</sup>	0.05	16 <sup>a</sup>	2.2	412 <sup>c</sup>	7.1	2.6	0.08
Parity	1	27.0 <sup>a</sup>	0.04	37.9	0.13	32.0 <sup>a</sup>	0.07	567 <sup>a</sup>	0.4	16.5 <sup>a</sup>	0.03	-	-	405	6.5	2.2 <sup>a</sup>	0.06
	2	29.5 <sup>b</sup>	0.06	37.7	0.17	32.9 <sup>b</sup>	0.09	609 <sup>b</sup>	0.5	18.5 <sup>b</sup>	0.05	-	-	404	6.7	2.7 <sup>b</sup>	0.07
	3	28.5 <sup>c</sup>	0.10	37.9	0.29	33.3 <sup>c</sup>	0.15	625 <sup>c</sup>	0.8	18.5 <sup>b</sup>	0.08	-	-	408	11.2	3.1 <sup>c</sup>	0.14

Different superscripts within a column denote significant differences between levels of same variables (P<0.001). Where: Milk Yield = daily milk yield per cow, Fat = milk fat content, Protein = milk protein content, Liveweight = lactating cow bodyweight, DMI = daily dry matter intake, INV = involuntary culling percentage, CI = calving interval, PD+ = number of services to attain positive pregnancy diagnosis.

#### *2.3.1.1 Production performance*

The effect of production system and parity on daily milk yield were both found to be highly significant ( $P<0.001$ ). All four systems were found to be significantly different to each other in terms of daily milk yield. LFS was observed to be the highest yielding system ( $\text{lsd}=34.9 \text{ kg day}^{-1}$ ,  $\text{sem}=0.06$ ) and HFC the lowest ( $22.8 \text{ kg day}^{-1}$ ,  $\text{sem}=0.07$ ), representing a difference of around 53%. Cows in LFC were higher yielding than HFS, thus the systems under LF regime were observed to be the two highest yielding systems. Peak milk yields were noted to occur in 2<sup>nd</sup> lactation, with an increase of around 9% from 1<sup>st</sup> lactation ( $P<0.001$ ), and a subsequent drop of around 3% into 3<sup>rd</sup> lactation.

Production system was found highly significant ( $P<0.001$ ) for both milk fat and protein content but there was no effect of parity on milk fat. Fat content was highest from HFS ( $39.9 \text{ g kg}^{-1}$ ,  $\text{sem}=0.19$ ) while the two systems with highest milk protein yields, HFS and LFS, were not significantly different to each other. Milk protein was found to increase in successive lactations ( $P<0.001$ ).

#### *2.3.1.2 Liveweight and feeding performance*

Effect of production system and parity upon animal liveweight were both highly significant ( $P<0.001$ ). The heaviest cows were found in LFS (623 kg,  $\text{sem}=0.5$ ), with HFC (574 kg,  $\text{sem}=0.5$ ) the lowest, almost 50 kg per cow difference. Cows in both groups managed under Low Forage regime were heavier than High Forage, and Select heavier than Control. Liveweight was also observed to increase with parity, and 3<sup>rd</sup> lactation cows were on average 58 kg heavier than 1<sup>st</sup> lactation cows ( $P<0.001$ ). Dry matter intake was significantly influenced by system and parity (both  $P<0.001$ ). LFS was found to have the highest DMI ( $19.4 \text{ kg day}^{-1}$ ,  $\text{sem}=0.05$ ) ( $P<0.001$ ) while Select consumed more than Control and LF more than HF. Although effect of parity was found significant, there was no significant difference in DMI between 2<sup>nd</sup> and 3<sup>rd</sup> lactations, following an increase of around 12% after 1<sup>st</sup> lactation ( $P<0.001$ ).

#### *2.3.1.3 Involuntary culling performance*

The rate of involuntary culling was found to be significantly influenced by system. Involuntary culling rate was considerably higher in LFS (31%, sem=2.2) ( $P<0.001$ ) than in the other three systems. HFC (10%, sem=2.2) had the lowest involuntary culling rate, but was not found to be statistically different either to LFC (18%, sem=2.2) and HFS (16%, sem=2.2).

#### *2.3.1.4 Fertility performance*

Calving interval and number of services to PD+ were the only two traits pertaining to fertility examined in this study. Production system effect was found to be significant on calving interval ( $P<0.001$ ) and there was no observed effect of parity. The shortest mean calving interval, LFC (393 days, sem=6.4), was found to be significantly different ( $P<0.001$ ) from the two longest, LFS (410 days, sem=6.6) and HFS (412, sem=6.4) but HFC (401, sem=6.5) was not significantly different to any of the other systems. There was no effect of system on the number of services to PD+, although parity was found highly significant ( $P<0.001$ ). Mean number of services required for pregnancy increased from 2.2 to 2.7 and 3.1 in successive lactations ( $P<0.001$ ).

### **2.3.2 Biological efficiency**

#### *2.3.2.1 Production efficiency*

Similar to the performance traits reported earlier, the interaction between production system and parity exerted the lowest influence of any term in the model upon all measures of biological efficiency. Effect of production system was found to be highly significant on all measures of production efficiency ( $P<0.001$ ), and effect of parity was found to be highly significant on all measures except for MS/DMI. LFS was observed to have the highest production efficiency of all the systems for each of the four production efficiency measures investigated (all  $P<0.001$ ). A breakdown of results for gross production efficiency is presented in Table 2.5.

**Table 2.5: Estimated production efficiency of Langhill cows presented as least squares means (lsm) with standard errors of the mean (sem).**

Variable	Level	ECM/LW		MS/LW		MS/DMI		Adj ECM	
		kg <sub>ECM</sub>	100kg <sub>LW</sub> <sup>-1</sup>	kg <sub>MS</sub>	100kg <sub>LW</sub> <sup>-1</sup>	g <sub>MS</sub>	kg <sub>DMI</sub> <sup>-1</sup>	kg <sub>ECM</sub>	cow <sup>-1</sup> yr <sup>-1</sup>
		lsm	sem	lsm	sem	lsm	sem	lsm	sem
System	LFC	4.4 <sup>a</sup>	0.03	0.32 <sup>a</sup>	0.003	0.12 <sup>a</sup>	0.002	8892 <sup>a</sup>	18.5
	LFS	5.3 <sup>b</sup>	0.03	0.39 <sup>b</sup>	0.003	0.13 <sup>b</sup>	0.002	10822 <sup>b</sup>	18.7
	HFC	3.9 <sup>c</sup>	0.03	0.28 <sup>c</sup>	0.002	0.11 <sup>c</sup>	0.002	6910 <sup>c</sup>	19.0
	HFS	4.4 <sup>a</sup>	0.04	0.32 <sup>a</sup>	0.003	0.12 <sup>a</sup>	0.002	7989 <sup>d</sup>	19.9
Parity	1	4.5 <sup>a</sup>	0.02	0.32 <sup>a</sup>	0.002	0.12 <sup>a</sup>	0.001	8301 <sup>a</sup>	13.5
	2	4.6 <sup>b</sup>	0.03	0.34 <sup>b</sup>	0.002	0.12 <sup>a</sup>	0.002	9006 <sup>b</sup>	18.0
	3	4.4 <sup>a</sup>	0.06	0.33 <sup>a</sup>	0.004	0.12 <sup>a</sup>	0.003	8653 <sup>c</sup>	30.5

Different superscripts within a column denote significant differences between levels of same variables ( $P < 0.001$ ). Where: ECM/LW = daily energy corrected milk yield per 100kg liveweight, MS/LW = milk solids (fat plus protein) per 100kg liveweight, MS/DMI = milk solids per kg dry matter intake, and Adj ECM = total annual energy corrected milk yield per cow adjusted for calving interval and lactation length

Raw milk yield per cow was earlier noted to be 53% higher in LFS than in HFC. However, when converted to ECM, correcting for fat and protein content of the milk, and accounting for the cows liveweight, ECM/LW<sub>100</sub> was found to be around 36% higher for LFS (5.3kg<sub>ECM</sub> 100kg<sub>LW</sub><sup>-1</sup>, sem=0.03) than HFC (3.9, sem=0.03). Under the same forage regime, LFS produced 20% more ECM per unit bodyweight than LFC (4.4, sem=0.03), and HFS (4.4, sem=0.04) 13% more than HFC. A similar result was observed for MS/BW, where LFS production efficiency was estimated to be 39% higher than HFC. When accounting for differences in feed intake, the margin between the two extreme systems was closer. However, LFS was 18% higher than HFC in terms of MS/DMI. When an adjustment for differences in calving interval and days in milk was applied to milk yield, LFS was found to have a total annual ECM yield per cow which was 56% higher than HFC (10822 vs 6910 kg<sub>ECM</sub> cow<sup>-1</sup> yr<sup>-1</sup>). In contrast to the raw milk yields trait, LFC and HFC were found to be not significantly different for all gross production efficiency measures, with the exception of Adj ECM.

#### 2.3.2.2 Energetic efficiency

The interaction of system and parity was found to contribute a comparatively very small proportion of the observed variation in the energetic efficiency. In both

measures of energetic efficiency the effect of production system and week of lactation were found to be significant ( $P<0.001$ ). The effect of parity was also found to be significant ( $P<0.01$ ). A breakdown of results for estimated energy efficiency is presented in Table 2.6.

**Table 2.6: Estimated biological energy efficiency of Langhill cows presented as least squares means (lsm) with standard errors of the mean (sem)**

Variable	Level	NE <sub>in</sub> /MS		NE <sub>lact</sub> /(NE <sub>in</sub> -NE <sub>m</sub> )	
		MJ kg <sub>MS</sub> <sup>-1</sup>		MJ MJ <sup>-1</sup>	
		lsm	sem	lsm	sem
System	LFC	74.3 <sup>a</sup>	0.79	0.941 <sup>a</sup>	0.0008
	LFS	66.1 <sup>b</sup>	0.80	0.951 <sup>b</sup>	0.0008
	HFC	77.3 <sup>c</sup>	0.78	0.908 <sup>c</sup>	0.0008
	HFS	71.2 <sup>d</sup>	0.82	0.919 <sup>d</sup>	0.0009
Parity	1	72.0 <sup>a</sup>	0.50	0.930 <sup>a</sup>	0.0005
	2	71.0 <sup>a</sup>	0.76	0.932 <sup>a</sup>	0.0008
	3	73.7 <sup>b</sup>	1.32	0.927 <sup>b</sup>	0.0014

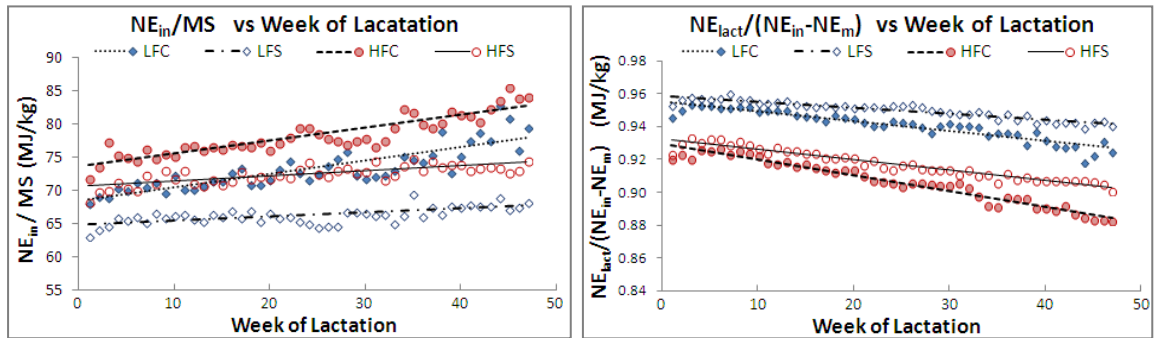
Different superscripts within a column denote significant differences between levels of same variables ( $P<0.001$ ). Where: NE<sub>in</sub>/MS = cows net energy intake required to produce 1kg of milk solids, and NE<sub>lact</sub>/(NE<sub>in</sub>-NE<sub>m</sub>) = the proportion of net energy utilised for milk production after accounting for maintenance

LFS (66.1 MJ kg<sub>MS</sub><sup>-1</sup>, sem=0.80) was estimated to be the most efficient system ( $P<0.001$ ) with respect to NE<sub>in</sub>/MS. HFC (77.3, sem=0.78) was found to be the least efficient. HFC was estimated to require 17% more net energy intake to produce each kg of milk solids than LFS. All four systems were found to be significantly different to each other. HFS (71.2, sem=0.82) was estimated to be more efficient than LFC (74.3, sem=0.79), the latter requiring around 4% more energy per kg milk solids. HFS required around 8% more energy than LFS, and HFC around 4% more than LFC.

Estimates of the proportion of net energy available for milk production after accounting for maintenance were found to be significantly different ( $P<0.001$ ) for all systems. LFS (0.951 MJ MJ<sup>-1</sup>, sem=0.0008) was found to have the highest estimate of NE<sub>lact</sub>/(NE<sub>in</sub>-NE<sub>m</sub>) and HFC (0.908, sem=0.0008) the lowest. In contrast to the NE<sub>in</sub>/MS, LFC (0.941, sem=0.0008) was found to be more efficient than HFS (0.919, sem=0.0008).

### 2.3.2.3 Change in efficiency over lactation

The interaction of system and week of lactation was found to be significant ( $P < 0.001$ ) in both measures of energetic efficiency. An interaction plot of system and week for each energetic efficiency measure is presented in figure 2.1. Linear regression lines were determined as most suitable fit to the data, and enabled demonstration of the consistent rate of change in efficiency throughout lactation. Detail of fitted linear regression lines is presented in Table 2.7.



**Figure 2.1: Biological energy efficiencies of Langhill cows plotted against week of lactation, with fitted regression lines**

**Table 2.7: Slope, intercept and  $R^2$  value of regression lines fitted for the biological energy efficiency of Langhill cows versus week of lactation**

Variable	Level	NE <sub>in</sub> /MS MJ kg <sub>MS</sub> <sup>-1</sup>			NE <sub>lact</sub> /(NE <sub>in</sub> -NE <sub>m</sub> ) MJ MJ <sup>-1</sup>		
		Slope	Intercept	R <sup>2</sup>	Slope	Intercept	R <sup>2</sup>
System	LFC	0.29 <sup>a</sup>	66.7	0.71	-0.00074 <sup>a</sup>	0.96	0.79
	LFS	0.12 <sup>b</sup>	63.9	0.38	-0.00047 <sup>b</sup>	0.96	0.73
	HFC	0.23 <sup>a</sup>	73.0	0.83	-0.00094 <sup>c</sup>	0.93	0.92
	HFS	0.09 <sup>b</sup>	70.4	0.66	-0.00064 <sup>a</sup>	0.93	0.90

Different superscripts within a column denote significant differences between levels of same variables ( $P < 0.001$ ). Where: NE<sub>in</sub>/MS = cows net energy intake required to produce 1kg of milk solids, and NE<sub>lact</sub>/(NE<sub>in</sub>-NE<sub>m</sub>) = the proportion of net energy utilised for milk production after accounting for maintenance

NE<sub>in</sub>/MS was observed to increase throughout lactation, therefore systems became less efficient, and rate of change was observed to differ amongst systems. Efficiency reduced at a lower rate in the Select systems, LFS and HFS, than in LFC and HFC ( $P < 0.001$ ). Over a standard 330 day lactation, NE<sub>in</sub>/MS was estimated to increase by around 5.5 MJ kg<sub>MS</sub><sup>-1</sup> and 4.1 MJ kg<sub>MS</sub><sup>-1</sup> (9% and 6%) for LFS and HFS respectively. In contrast, net energy requirements for LFC and HFC over the same period increased by 13.5 MJ kg<sub>MS</sub><sup>-1</sup> and 10.4 MJ kg<sub>MS</sub><sup>-1</sup> (20% and 14%) respectively. At

around week 18 of lactation, HFS was observed to become more efficient than LFC with respect to  $NE_{in}/MS$ .

A reduction in  $NE_{lact}/(NE_{in}-NE_m)$  was observed for all systems throughout lactation. The rate of this change was greatest in HFC ( $P<0.001$ ), dropping by around 4.5% over 330 days lactation. LFS became less efficient at a significantly slower rate than other systems ( $P<0.001$ ) and was estimated to reduce by around 2.4%. There was no significant difference between LFC and HFS in terms of rate of change in  $NE_{lact}/(NE_{in}-NE_m)$ , and both systems reduced the proportion of net energy allocated to milk production by around 3.5% over a lactation.

## 2.4 Discussion

The aim of this chapter was to examine differences in performance traits describing lactating cows from four conventional dairy production systems, and to investigate differences in production efficiency and energetic efficiency of the four systems. Analysing performance traits in the same context as production efficiency has important implications for the way in which estimated efficiencies of dairy production systems are interpreted. This permitted an examination of whether systems with high milk production were more efficient in terms of their overall productivity, and throughout the course of lactation.

### 2.4.1 Performance traits

#### *2.4.1.1 Production, liveweight & feeding*

Overall the cows in the LFS system were found to be the heaviest, with greatest feed intake and highest productivity. This is perhaps to be expected when considering that cows were genetically selected for potential for production, and results were broadly in line with those determined in other recent studies involving the Langhill herd (Chagunda et al., 2009; Bell et al., 2010).



#### *2.4.1.2 Fertility*

Wall et al. (2007) noted that bigger animals were negatively associated with fertility, and a negative association between genetic selection for productivity and traits for reproduction and health has been frequently observed (Pryce et al., 1999; Veerkamp et al., 2001; Miglior et al., 2005). However, this analysis found that there was no difference amongst systems in the mean number of services required to achieve PD+, although cows were found to require greater number of services with increasing parity. Both systems with the Select genetic line were observed to have the longest calving intervals, but these were only found to be significantly different to the LFC system. The absence of an observable difference in fertility traits between systems can perhaps be attributed to farm management policy. Systems were managed strictly in a 3 lactations programme, and protocol for the Langhill herd was such that all cows were permitted to receive up to seven services in order to achieve PD+, otherwise being transferred from the herd. Thus the estimated means for services to PD+ can only account for cows which were successfully impregnated and subsequently remained in the Langhill systems. The strict management policy may also dictate that while performance can be compared between systems, care is needed when comparing with other studies may which contain older animals and are managed by different herdsmen.

#### *2.4.1.3 Involuntary culling*

The involuntary culling rate, however, was significantly greater ( $P < 0.001$ ) in LFS (31%) than in the other three systems. This result is consistent with those that were reported by Roberts and Beattie (2010), who estimated involuntary culling rates to be 21, 28, 10 and 23% for LFC, LFS, HFC and HFS respectively over a four year period from 2006. Those figures were broadly consistent with the results of this study, although the margin of difference between LFS and the other systems was estimated to be greater over the longer period covered in this analysis. Haskell et al. (2006) noted that cows under fully housed systems, such as LF in the present study, displayed increased risk of lameness and leg injury. However, Chiumia et al. (2013) noted that the main reasons for culling multiparous cows from Langhill were fertility and udder problems, whilst the majority of 1<sup>st</sup> lactation heifers were culled for fertility reasons alone. Both fertility and udder problems were more than twice as

likely reasons for culling as foot/leg health problems (Chiumia et al., 2013). Treatments such as regular foot trimming, foot bathing and access to soft standing areas are known to improve foot health (Blowey et al., 1993; Vokey et al., 2001). It is likely that routine management with these mitigating treatments led to low incidence of lameness in the Langhill herd (Mason, 2013). The lowest involuntary culling rate, observed in HFC, was found not significantly different to both LFC and HFS. Pryce et al. (1999) found that fertility and health were deteriorating in cows as genetic merit for production increased, but found no effect of interaction between genetic merit and feeding regime. In the present study however, the significantly higher rate of culling observed in LFS suggests that this issue could be a consequence of the interaction between LF regime and Select genetic line, of which the system is representative. Maas et al. (2009) noted that if annual dairy cow culling rates increase above 30% there would be a resulting unsustainable deficit of replacement female numbers in the future. The considerably higher rate of involuntary culling in LFS casts doubt on the long term sustainability of this system, as any further increase in culling rate will begin to inhibit the ability of LFS cows to raise sufficient replacement heifers. Modern breeding indices offer genetic selection for health traits and fertility as well as milk yield (Wall et al., 2003), thus this may enable a more sustainable genetically improved herd in future. Long term sustainability should become a priority for research into the Langhill systems in future.

#### 2.4.2 Biological Efficiency

##### *2.4.2.1 Production efficiency*

In terms of production efficiency, the LFS system was found to be the most efficient in all four categories assessed. The fact that LFS was observed to be the leading system in terms of ECM/LW, MS/LW and MS/DMI despite also having the highest average liveweight and highest DMI of the four systems, emphasises the considerable margin between LFS and the other systems in terms of milk production. Dairy cows are known to mobilise body reserves in early lactation, coinciding with peak milk yield, and replenish these reserves either later in lactation or during their dry period (Coffey et al 2004; Prendiville et al., 2009). Wall et al. (2007) reported

that higher producing cows were more likely than lower producers to utilise body reserves at the peak of lactation. This may explain why LFS was able to maintain the highest gross production per unit liveweight and per unit DMI, and Select cows were able to produce greater yields than Control under the same feeding regime. However, there was no significant difference found between LFC and HFS in terms of ECM/LW, MS/LW or MS/DMI. It is perhaps surprising to find no difference between these two systems, considering that DMI was estimated to be 9% higher in HFS than LFC, while at the same time liquid milk yield was estimated to be 10% lower per cow in HFS. However, milk solids production was significantly higher for HFS, yielding 12% more fat and 5% more protein per kg raw milk than LFC. Thus HFS appeared to be more efficient in terms of production efficiency when accounting for milk solids. This supports the argument that these measures of production efficiency may not accurately reflect the true efficiency of dairy production systems (Veerkamp et al., 1995). Measures of production efficiency employed in the present analysis (ECM/LW, MS/LW, MS/DMI) have all been previously defined and employed in previous studies (Prendiville et al., 2009). Veerkamp et al. (1995) noted, however, that being simply a ratio of two quantities (output versus input), production efficiency is therefore a measure of gross efficiency, and takes no account of energy apportioned to other processes besides milk production within the body, such as maintenance. Prendiville et al. (2009) stated that from a practical perspective, net energy must be a key determinant of production efficiency.

#### *2.4.2.2 Energetic efficiency*

Biological efficiency in terms of net energy was estimated in two ways; the net energy intake required to produce 1kg milk solids ( $NE_{in}/MS$ ) and the proportion of net energy utilised for milk production after accounting for maintenance ( $NE_{lact}/(NE_{in}-NE_m)$ ). The profiles for both measures of energetic efficiency were favourable in early weeks of lactation but efficiency was reduced steadily as lactation progressed. Thus the efficiency profiles for the four systems in the present study were broadly consistent with those previously reported for Holstein-Friesian cows throughout lactation (Prendiville et al., 2010, Veerkamp and Emmans, 1995). However, overall LFS was found to have the lowest  $NE_{in}/MS$ , and HFS was also

found significantly more efficient than LFC. Cows in LFC required 12% more net energy intake than LFS to produce a kilogram of combined milk solids under the same low forage management regime. Under the high forage regime, HFC required around 9% more net energy than HFS to produce 1 kg milk solids. It was noted that as lactation progressed, both the systems with Control genetic lines became less efficient at a faster rate than the two Select systems. Thus not only were the Select systems able to continue producing at a higher level, but the disparity between energetic efficiencies of the two genetic lines widened as lactation progressed. This observation supports the conclusions of Coffey et al. (2004) who noted that animals selected for high productivity did not replenish all of their body reserves which were mobilised in early lactation. In the present study, systems with Select genetic line were thus observed to maintain consistently higher rate of production and energetic efficiency into late lactation at the expense of replacing body reserves. The observed rates of change in  $NE_{in}/MS$  also suggest that over the course of lactation, although operating at different levels of efficiency, the rate of reduction in gross energetic efficiency was comparable for cows of a particular genetic line under different feeding regimes.

LFS was estimated to have also apportioned the highest amount of net energy for milk production, with both LFS and LFC significantly higher in terms of  $NE_{lact}/(NE_{in}-NE_m)$  over a lactation than the two high forage systems. Although net energy apportioned to milk declined throughout lactation, LFS continued to apportion a significantly higher level, leading this system to further diverge from the other systems in terms of energetic efficiency. At the beginning of lactation HFC allocated the lowest proportion of net energy to milk production and also followed a divergent trend from the other systems. The high proportion of energy given to lactation by LFS lends further support to the premise that the highest producing cows divert resources to production at the expense of their own welfare, especially when considering the previously noted rate of involuntary culling.

A previous study reported the variation between different breeds of dairy cattle with respect to productivity and energetic efficiency profiles throughout lactation. Prendiville et al. (2010) found that Holstein-Friesian cows were less efficient

compared to Jersey cows in early lactation but became comparatively more efficient as lactation progressed. However, in the present study four different conventional Holstein-Friesian dairy production systems were found to display significantly different energetic efficiency profiles. This result highlights the potential for variation in biological efficiency that exists within the breed under different genetic selection and management conditions. All four systems were estimated to be more efficient than the extensive Holstein-Friesian grazing systems reported by Prendiville et al. (2009) and Coleman et al. (2010) in terms of gross production efficiency as well as  $NE_{in}/MS$  and  $NE_{lact}/(NE_{in}-NE_m)$ . Veerkamp et al (1994) assessed the performance and efficiency of the Langhill systems 18 years ago, but the systems were located on a different farm and under different feeding regimes. Nonetheless, the Langhill genetic lines have remained intact since that study and offer some comparison and assessment of the evolution of the Langhill lines. Veerkamp et al. (1994) observed that there was no significant difference between genetic lines in terms of their DMI, although production and energetic efficiencies were greater in the Select cows owing to significantly greater productivity. Annual milk yields were found to range from around 4500 to 6000kg cow<sup>-1</sup>. This is considerably lower than the present Langhill systems in this analysis. However, the 1994 study found that in terms of gross energetic efficiency Select cows were more efficient than Control on both high and low concentrate diets, and that Select line maintained an advantage even after correcting for liveweight, lactation and maintenance (Veerkamp et al., 1994). Although employing a different measure of energetic efficiency, the conclusions reported by Veerkamp et al. are broadly comparable with the findings of the relative efficiencies of Langhill systems in this analysis.

In this chapter, the efficiency of four dairy production systems has been defined by the biology and productivity of the livestock within the herd. However, while analysis of cows' gross productivity and net energy profiles is a valid method, there is a need to go further. In order to take account of the true overall efficiency of dairy production at systems level, a more comprehensive approach such as Life Cycle Analysis (LCA) is desirable. The LCA can incorporate the biological efficiency along with efficiency of resource use, crop production and the associated

environmental impacts of dairy production. In this way a more balanced perspective of the long term sustainability of dairy production systems would be obtained.

## 2.5 Conclusions

The results of this study found significant differences in Holstein-Friesian performance traits amongst four dairy production systems within the same farm. The reputed greater feed intake, body weight and gross productivity of genetically selected cows were confirmed in this analysis. The LFS system was found to be the most efficient system in every examined category of production efficiency and energy efficiency. Similarly the HFC system, the system most representative of a high yielding conventional UK dairy farm, was estimated to be the least efficient in terms of gross productivity and energetic efficiency. Significant differences were observed amongst systems with respect to the rate of change in production and energetic efficiencies throughout lactation. Biological efficiency of a conventional dairy production system throughout lactation can therefore be optimised by combination of management regime and improved genetic merit. A significantly higher rate of involuntary culling was also observed for LFS system, introducing a question over the long term viability of the system despite its evident superior production efficiency.

## **Chapter Three**

## Chapter 3

### **The effect of forage regime and cattle genotype on the balance of global warming potential in a conventional dairy farm**

#### 3.1 Introduction

##### 3.1.1 Background

There has been increasing attention paid during the past decade to the contribution of food production to climate change and the challenge faced by society's current demand for products such as meat and dairy. The Food and Agriculture Organisation of the United Nations (FAO) reported in 'Livestock's Long Shadow' that agriculture contributed around 18% to the total global anthropogenic greenhouse gas (GHG) emissions (Steinfeld et al., 2006). A further study by the FAO defined the contribution of dairy production systems to be 2.7% globally, with an additional 1.3% attributed to its associated beef output (Gerber et al., 2010).

In passing the Climate Change (Scotland) Act 2009, the Scottish Government committed to an 80% reduction in national GHG emissions by 2050 (compared to 1990 baseline levels), with an interim target of 42% by 2020 (Scottish Government, 2009a). In Scotland agriculture is estimated to contribute around 16% of the total annual GHG emissions (Thomas et al., 2011), while dairy farms presently contribute around 2.5% of the national total (Sheane et al., 2011). The Scottish Climate Change Delivery Plan (Scottish Government, 2009) set the agricultural sector a target to reduce emissions by 1.3 Mt CO<sub>2</sub>e by 2020, also equivalent to the 42% reduction, although the dairy industry was not charged with a specific individual target under the plan. However, the large scale of emissions means that any potential improvements made in the GWP of dairy production systems will make a substantial contribution towards attaining the government's ambitious climate change targets. If the dairy industry is to meet the growing global demand for dairy products, ways to minimise GHG emissions per unit product will become increasingly important (Steinfeld et al., 2006).



### 3.1.2 Greenhouse gas emissions from dairy production systems

Component GHGs contributing to the total global warming potential (GWP) of dairy production systems arise from processes both on and off the farm. The ratio of these GHGs differs significantly from that in other industry sectors (Flysjö et al., 2011) as the dominant emission is not carbon dioxide ( $\text{CO}_2$ ) related to energy and fossil fuels. In the dairy sector, the dominant GHG emitted is methane ( $\text{CH}_4$ ), contributing around 52-65% of the total GWP of conventional dairy production systems (Cederberg and Mattsson, 2000; Haas et al., 2001). Methane arises as a by-product from microbial breakdown of carbohydrates in the digestive tracts of ruminant animals. This process, called enteric fermentation, is influenced by the animal's production level, feed composition and the type of feed consumed (Cederberg and Flysjö, 2004; Chagunda et al., 2009; Garnsworthy et al., 2012). Enteric  $\text{CH}_4$  accounts for around 43% of the total GHG emissions from the Scottish dairy sector (Sheane et al., 2011). Further  $\text{CH}_4$  emissions arise from the anaerobic bacterial fermentation of animal manures, mainly from storage of slurry in a liquid system. Together, enteric fermentation and manure represent some 80% of global agricultural methane emissions and about 30 to 40% of the total anthropogenic methane emissions (Steinfeld et al., 2006).

The second greatest contributing GHG from the dairy sector is nitrous oxide ( $\text{N}_2\text{O}$ ), with emissions comprising around 25-32% of the total GWP of conventional dairy production systems (Cederberg and Mattsson, 2000; Haas et al., 2001; Saunders and Barber, 2009). Emissions of  $\text{N}_2\text{O}$  arise both directly and indirectly from multiple on farm sources (de Boer, 2003). Direct  $\text{N}_2\text{O}$  emissions result from deposition of manure and urine on pasture, the storage of farm manure and slurry, the application of manure and chemical fertilisers to crops and from decomposition of crop residues in the soil. Indirect emissions of  $\text{N}_2\text{O}$  arise from the volatilisation and subsequent re-deposition of ammonia from applied fertilisers and manures, and as a result of leaching and runoff from agricultural soils (IPCC, 2007). Carbon dioxide results mainly from the combustion of fossil fuels on the farm and in the processes surrounding external production and transport of purchased feeds and fertilisers. Emissions of  $\text{CO}_2$  also arise from land use change, such as the conversion of forest to productive agricultural land, particularly relevant to global dairy industry in the case

of South American production of soy meal (Flysjo et al., 2012). The dynamic relationship between the working and natural processes of a dairy production system leads these three GHG to be inexorably linked. Compared over a standard 100 year period, the GWP of CH<sub>4</sub> and N<sub>2</sub>O are estimated to be 25 and 298 times greater respectively than that of CO<sub>2</sub> (IPCC, 2006). Thus even a small shift in the balance of these GHG emissions produced may lead to a substantial difference in overall GWP.

Although the greatest impact on reducing farm emissions at national level could be achieved by decreasing the country's current population levels of animals, this would be potentially self defeating. At present, less than 1% of raw milk available for consumption in the UK is imported (DairyCo, 2012a). By imposing a limit on domestic production, however, retailers would have to source imported produce to satisfy demand, unless there was a shift towards lower consumption patterns. In turn this imported produce could lead to potentially even higher GHG emissions per unit of product. Steinfeld et al. (2006) noted that the most promising approach for reducing emissions from livestock systems is by improving the productivity and efficiency of livestock production through better nutrition and genetics. It has been shown that high yielding dairy cows with high feed intakes are associated with a lower enteric CH<sub>4</sub> output per unit milk (Garnsworthy, 2004; Casey and Holden, 2005b; Bell et al., 2010), therefore herd numbers may be optimised for level of production. However, Chagunda et al. (2009) showed that although increasing milk production was associated with a reduction in enteric CH<sub>4</sub> per unit milk, excreted nitrogen could increase both per unit milk and per hectare of land used depending on the genetic merit of animals and the specific details of the production system. It has also been demonstrated that while implementing an organic system can reduce overall emissions of CO<sub>2</sub> and N<sub>2</sub>O, the reduction in GWP may be nullified by lower production and an inherent overall increase in enteric CH<sub>4</sub> (de Boer, 2003). Weiske et al. (2006) also noted that, due to the trade-offs amongst dairy GHG emissions, many mitigation measures suggested in the literature do not always result in the expected reduction potential when evaluated at the farm level. The overall GHG pollution potential from dairy production systems is therefore a dynamic process which should be assessed at a whole systems level in order to optimise the balance of

the total output of pollutants against productivity. This whole system analysis can be performed using Life Cycle Assessment (LCA).

### 3.1.3 Life Cycle Assessment

Life Cycle Assessment stands today as the pre-eminent tool for estimating environmental effects caused by products and their processes (Reap et al., 2008), favoured for being very adaptable and for its capability in accounting for all aspects of a process from the 'cradle to the grave'. In dairy production systems this comprises the life cycle required for the production of raw milk and associated co-products within a specified boundary, from 'cradle to the farm gate'. Environmental accounting therefore includes emissions from both the on- and off-farm production of system inputs, and the on farm processes and management practices leading up to the product leaving the farm-gate. Over the past decade, studies have been undertaken at system level examining the relationships between GHG in dairy farms. Many studies have been aimed towards demonstrating the application of LCA methods in dairy farming (Hospido et al., 2003; Thomassen and de Boer, 2005; O'Brien et al., 2011) or focussed on a specific dairy product output (Berlin 2002). Furthermore, studies assessing a whole farm system have been conducted using LCA mainly in the context of providing a comparison between the environmental efficiency of conventional and organic systems (Cederberg and Mattsson, 2000; Haas et al., 2001; de Boer, 2003; Thomassen et al., 2008b), or between typical systems at a national level (Cederberg and Flysjö, 2004; Basset-Mens et al., 2005; Casey and Holden, 2005a; Saunders and Barber 2007). In the UK, Williams et al. (2006) used LCA to model national data and compare the environmental impacts of alternative methods of dairy production, such as increasing milk yield of the national herd and reducing Autumn calving numbers. Although methods of agricultural LCA have been well defined, studies vary considerably in their level of detail, definition of system boundaries, emissions factors and allocation techniques (Gerber et al., 2010; Yan et al., 2011). Thus the strength of drawing direct comparisons at dairy systems level between the results of different studies has in the past been questionable (Basset-Mens, 2008).

### 3.1.4 Aims and objectives

Although fundamentally similar in their application of LCA to examine dairy farming by way of GHG emissions per unit of productivity, studies at systems level have not examined in depth the potential for variation amongst conventional dairy systems within the same geographic region. The first objective of this chapter is to assess by way of LCA the GWP of four dairy production systems within a conventional farm. In this way the estimated environmental efficiencies of dairy production are directly comparable at systems level. The four systems comprise two feeding regimes applied to each of two genetic lines, thus the systems are representative of the interaction between forage regime and genetic line. The second objective of the study is to examine the effect of uncertainty in farm-derived data and emissions factors on the estimated GWP of the dairy production systems by performing sensitivity analysis. These two objectives will provide a robust comparison of the environmental efficiency four dairy production systems.

## 3.2 Materials and Methods

### 3.2.1 Systems Description

The study was based on Scotland's Rural College's (SRUC, formerly Scottish Agricultural College) established long-term Holstein-Friesian genetic and management systems project, situated at SRUC Dairy Research Centre, Crichton Royal Farm, Dumfries. Data used were collected over a period of seven years, from January 2004 to December 2010, and incorporated specific details of four distinct dairy production systems within a conventional farm. In the production systems study, animals were maintained in two feeding regimes; High forage (HF) and Low forage (LF). The HF regime aimed to provide 75% by dry matter (DM) of the herd's total mixed ration (TMR) diet when indoors from home grown forage crops (ryegrass silage, whole crop maize, wheat alkalage) and the remainder of the ration composition coming from purchased concentrated feeds (including: distillers grains, rapeseed meal). In addition, cows in the HF animals were turned out to graze ryegrass pasture when available, and therefore the total home grown element of the

HF cows' annual diet was greater than 75%. In contrast, the LF groups were fully housed; the herd retained indoors all year round and fed a TMR comprising approximately 45% by dry matter of home grown forages, with 55% from purchased concentrates (including: wheat, distillers grains, sugar beet pulp, soya hulls) imported onto the farm (Chagunda et al., 2009). Within each forage regime, animals comprised two contrasting genetic lines. Control (C) animals were bred to be of average UK genetic merit for milk fat and protein production, and Select (S) animals represented the top 5% of UK genetic merit (Pryce et al., 1999). Maintaining the specific details of these groups in the long term genotype x feeding regime project resulted in four divergent dairy production systems – HFC, HFS, LFC and LFS (Chagunda et al., 2009). These systems are representative of the interaction between forage regime and genetic line, and also offer a representative cross-section of existing and potential dairy production systems in the UK. Animals were managed in a 3 lactations programme before moving out of the systems study, with all-year round calving, and herd numbers maintained at approximately 50 cows in each group. The 3 lactations management was considered applicable to UK dairy systems as the average dairy cow lifespan is noted to be 3.3 lactations (FAWC, 2009). Livestock were not permitted to change production systems, therefore upon entering one of the four trial systems for their first lactation, cows remained in that system for the rest of their life in the Langhill herd. Cows were milked three times daily, received equal treatment regarding health and fertility and were under responsibility of the same herdsman. Select and Control cows were managed together and groups retained in the same building when housed. Young stock from all groups were managed together and fully housed. A selection of system traits and characteristics describing the four dairy production systems is presented in Table 3.1.

**Table 3.1: Langhill dairy production systems described by system characteristics**

Characteristic	Units	Production System							
		LFC		LFS		HFC		HFS	
		mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Milk fat	g kg <sup>-1</sup>	35.5	6.98	38.0	7.43	38.7	6.45	40.5	7.10
Milk protein	g kg <sup>-1</sup>	31.4	3.59	33.4	3.94	31.7	3.89	33.3	4.35
DMI	kg day <sup>-1</sup>	17.6	4.03	19.9	4.46	17.4	4.17	19.1	4.61
Dietary CP	kg day <sup>-1</sup>	3.22	0.32	3.62	0.37	2.94	0.34	3.22	0.38
MEI	MJ day <sup>-1</sup>	200	47.4	226	52.9	196	49.1	215	53.6
Cow liveweight	kg	616	76.2	631	79.3	588	75.4	613	80.5
Calving interval	days	388	53.3	407	72.3	396	57.7	407	72.5
Involuntary cull	%	18	4.5	31	7.7	10	5.0	16	6.2

Where: LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select; DMI= dry matter intake, MEI = metabolisable energy intake, CP = crude protein

### 3.2.2 Data collection

All farm data were sourced from the SRUC Langhill database unless otherwise stated. Langhill data were recorded and screened by the experienced team of staff and technicians at CRF before being validated and confirmed into the database by the SRUC database manager in Edinburgh. Subject data were categorised amongst system inputs (livestock, land, silages, energy use, fertilisers, imported feeds) processes (farm activities, management) and outputs (productivity, crops, manure), and then summarised by calendar year for LCA calculations.

#### 3.2.2.1 *Herd dynamic*

The yearly population, movement of animals between age and physiological groups, and the fate of individual animals was accounted for in the herd dynamics part of the LCA model. Herd dynamics were constructed for each system in each year of the study period in order to account for livestock being replaced in the systems, and to account for the periods for which these animals persisted on the farm. Animals were segregated into different livestock categories defined by their by age, sex and, in the case of lactating cows, their parity. United Kingdom livestock units (LU) were used to equate different categories of livestock, whereby the number of animals in each category was multiplied by a correction factor. These were defined for bull calves, heifers aged 0-12 months, heifers 12-24 months and heifers over 24 months, as being 0.34, 0.34, 0.65 and 0.80 respectively (DEFRA, 2010). Factors for cows were corrected for average liveweight and milk yield (ADAS, 1983), and defined as 1.48, 1.64, 1.26 and 1.37 for LFC, LFS, HFC and HFS respectively. Furthermore, the livestock were defined by their movements throughout the year, for example dried-off, calved, culled or dead. From this herd dynamic the number of LU present on the farm and in each age category were determined for each year.

#### 3.2.2.2 *Productivity*

Cows were milked three times every day. Milk yields were recorded for individual cows at every milking session. Data on milk composition (fat, protein and somatic cell count) were recorded from samples collected from each cow once a week. Liveweights were recorded daily for cows after every milking and recorded weekly for dry cows, heifers and young stock.

### 3.2.2.3 Diet formulation and feeding

Animals were fed specific diets depending on their production system, age and, when older, their stage of pregnancy. During the winter period when all cows were indoors, lactating cows were fed a total mixed ration (TMR) comprising three homegrown forages (ryegrass silage, wholecrop wheat alkalage and wholecrop maize silage), a purchased feed blend and minerals. Purchased HF blend contained rapeseed meal with wheat and barley distillers grains. The purchased LF blend contained crimped wheat, distillers grains, sugarbeet pulp molasses, soya meal and minerals. Feed was offered once a day to each group and ration formulation was recorded to the nearest kg. Lactating cows also received a supplemental 0.25 kg of concentrates each in the milking parlour at every milking. When drying off at the end of a lactation, cows were initially fed a specific drying-off diet, followed by either a high-forage or low-forage transition-period feed. The transition period was the three weeks prior to predicted calving date. The transition diet comprised one-third of the lactating cow TMR plus 5kg wheat straw. Specific details of the Langhill TMR formulations (HF and LF) are shown in Table 3.2.

**Table 3.2: Total Mixed Ration (TMR) components expressed as percentages (%) of the total formulation offered to lactating cows under High forage (HF) and Low forage (LF) groups and to dry cows**

Feeding Regime	High Forage %	Low Forage %	Dry Cows %
TMR Component			
Ryegrass Silage	27.0	45.0	30.0
Wholecrop Wheat Alkalage	9.0	15.0	10.0
Wholecrop Maize Silage	9.0	15.0	10.0
Purchased Concentrate/Blend	53.9	24.2	4.1
Wheat Straw	-	-	45.0
Minerals	1.1	0.8	0.9

Daily TMR intake of individual lactating cows was recorded 3 days out of every 6 using automated HOKO feeding gates (Insentec BV, Marknesse, The Netherlands), with animals feeding from behind a strap on the alternate 3 days. In the summer period, LF cows continued to be fully housed and received the TMR, while HF cows were outdoors grazing pasture. Feed intake of HF cows at pasture could not be measured in the same way as the TMR, however the number of days and time

periods of those days spent outside were recorded. In a previous study on the Langhill herd, Bell et al. (2010) estimated the average dry matter intake (DMI) of HF cows grazing pasture to be 19.2 kg day<sup>-1</sup> for Control and 20.8 kg day<sup>-1</sup> for Select cows, based on the cows' energy balance. These figures were employed in calculations for the present study.

Young stock were managed together on the same diet irrespective of their system, while their feed composition changed and feed intake increased regularly in line with the animals' growth and age. A typical diet for young stock, from birth to the pre-calving transition period, was derived using information and daily feed sheets obtained from the CRF Farm Office, in consultation with the senior dairyman at CRF (Kelly, 2010) and suggested guideline diets in the Farm Management Handbook (Craig and Logan, 2012).

Samples of all forages and rations were collected weekly and sent to SRUC Analytical Services Department, Bush Estate, Penicuik. Laboratory analysis included the DM content of samples, metabolisable energy (ME) content, crude protein (CP) content and digestibility of feeds.

#### *3.2.2.4 Fertiliser application*

Over the study period, Crichton Royal Farm employed a combination of organic and manufactured fertiliser applications on crops grown on-farm for animal feed. Type of fertiliser and method of application were determined by the Farm Manager according to the specific crop, field and long term nutrient management plan at CRF, resulting in variation between years. Organic fertiliser was applied as both liquid slurry and solid manure at CRF. Several methods were employed for liquid applications, for example utilising a splash plate, trailing shoe or shallow injection depending on crop and circumstance. Through implementation of slurry injection, CRF operated an efficient organic fertiliser management practice, reducing the quantity of manufactured fertiliser required. Data were recorded on the application rate and type for each field. Despite operating with increased slurry efficiency, manufactured fertilisers were still applied to crops and pasture, in common with conventional farming system practice. These included urea, ammonium nitrate and a range of NPK fertilisers. Data were recorded on field and crop type, fertiliser type, content, quantity and application rate.



#### *3.2.2.5 Energy use*

Electricity consumption was determined from energy invoices obtained from the CRF farm manager's office. All tractors and other farm machinery, which included feed mixers and generators for slurry pumping, ran on red diesel. Fuel use, including that used by contractors, was recorded to the nearest litre for each daily farm activity. Examples of these activities were daily feeding, ploughing, harvesting forage crops and applying fertilisers.

#### *3.2.2.6 Management of liquid and solid manures*

Management of manures fell into three categories – liquid storage, solid storage and deposition at pasture. Liquid system manure was contained in a reservoir underneath the main steading before pumping into storage in two uncovered outdoor slurry tanks, while solid manure was collected daily and stored in an uncovered outdoor midden. All stored slurry and manure was subsequently retained on-farm and applied to land as organic fertiliser. As the LF milking cows were continually housed throughout the year, all of their manure was transferred into a liquid slurry storage system. HF cows spent only the winter period (typically November to March) in a fully liquid storage system and deposited excreta at pasture for the remainder of the year. Proportions of HF manure deposited either into liquid storage or at pasture in a given year were determined by the total time spent at pasture in a given year. Daily manure from the milking parlour from all groups was also collected throughout the year in the liquid storage.. All young, dry and transition cows were fully retained indoors where their manure was managed as solid storage farm yard manure (FYM).

#### *3.2.2.7 Forage crops and land use*

Animal feeds produced on-farm at CRF comprised three forage crops: ryegrass silage, wholecrop wheat alkalage and wholecrop maize silage. Harvest yields from all three crops were retained on farm to be used as forages for indoor feeding, with additional improved land employed as ryegrass pasture for grazing. Ryegrass silage was harvested in three cuts, typically in April, July and September, although some fields were subject to fewer cuts depending on management for grazing or instances of 'double cropping'. In the latter case, following a first cut of grass silage, the land was sown with maize. Wheat was harvested in August and maize generally harvested in late September and early October, although slightly later when a field was 'double

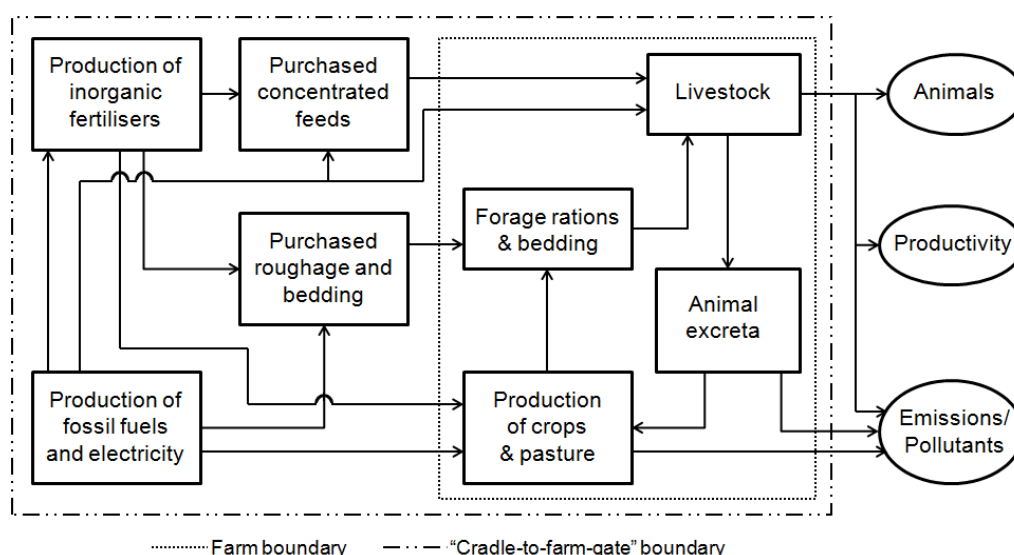
cropped'. All harvested crops were stored in covered outdoor silage clamps and unloaded by block cutter as required. Harvest yields were recorded at ensilage as trailer loads were deposited into the clamp, and samples collected to determine the DM% at ensilage. Dry matter losses were considered during harvesting (categorised as mechanical, respiration, wilting and leaching losses), ensiling (surface, effluent and invisible losses) and unloading (mechanical losses) of forages (Bastiman and Altman, 1985; MacDonald et al., 1991).

### 3.2.3 Goal and scope definition

The goal and scope phase of LCA included the definition of system boundaries, the functional unit (FU), approach to co-product allocation and relevant environmental impact categories. Although this study broadly follows the methodological guidelines of PAS:2050 (BSI, 2011), this study does not claim to be fully PAS:2050 compliant. The goal and scope details specifically the factors included in the LCA.

#### 3.2.3.1 Boundaries

The boundary of the current LCA was defined as from 'cradle to gate' (BSI, 2011), covering the stages from the extraction or acquisition of raw materials up to the point at which the product milk left the farm. A flow diagram displaying the on- and off-farm processes included within the LCA boundary is presented in figure 3.1.



**Figure 3.1: Flow diagram showing Langhill dairy production system boundaries**

This ability to include off-farm processes, as well as on-farm, gives the LCA a powerful advantage over simpler on-farm emissions centred approaches to GHG accounting for analysis at production systems level. The LCA boundary in the present study incorporated the major GHG emissions associated with the off-farm production and transportation of fossil fuels, electricity, purchased concentrated feeds, bedding and manufactured fertiliser. On-farm system inputs included use of fossil fuels, application of fertilisers, land use, cropping, livestock, feed rations and the management of animal manures. Energy required for cooling and storage of raw milk prior to leaving the farm was included, but the study did not therefore account for the subsequent processing and transport of consumer dairy products. However, this approach was considered appropriate because 80% of dairy product GHG emissions are associated with the production phase (Yan et al., 2011). Furthermore, the product raw milk from the four Langhill systems went on to be treated equally in post-farm processing. The study did not take account of capital goods, such as the purchase and upkeep of buildings, machinery and of farm personnel. Inputs such as medicines, seeds, detergents and disinfectant were excluded because of their minimal impact upon the system (Cederberg, 1998). The study also did not account for purchased semen for artificial insemination, nor the management and disposal of dead stock. No account was made of carbon sequestration in this study. The time frame of each assessment was one calendar year, removing any influence of seasonality.

#### *3.2.3.2 Functional Unit*

The FU describes the primary function fulfilled by a product system and enables results from different systems to be treated as functionally equivalent (Guinée et al. 2002). The primary function of dairy systems is milk production and the FU chosen was ‘one kg of energy corrected milk (ECM) leaving the farm gate’ (Cederberg and Mattsson, 2000). Energy corrected milk employs a correction used by the dairy industry to consider both the fat and the protein content of the milk. Following Sjuanja et al. (1990), the equation used in this study was:

**Equation 3.1** 
$$\text{ECM (kg)} = 0.25\text{M} + 12.2\text{F} + 7.7\text{P}$$

where M = milk yield (kg), F = fat content (kg), P = protein content (kg)

### *3.2.3.3 Allocation to co-products*

Allocation describes how outputs such as GHG are partitioned between the product of interest (milk) and any co-products. This has been a key issue in previous LCA of dairy production, noting that the allocation method can have significant influence upon the estimated product emissions (Cederberg & Stadig, 2003). In this study all forage crops and manure were retained on the farm (McClymont, 2011), therefore the value of surplus and culled livestock was defined to be the only co-product.

Several methods of allocating this value are available in the literature. These include, in order of preference: system expansion, physical/biological causality, composition and mass allocation, economic allocation, and no allocation (Audsley et al., 1997). Rotz et al. (2010) state that the no allocation option creates an unfair bias against milk production, while the system expansion approach creates an unfair bias in favour of milk production. Many studies have employed an economic value of 85% allocated to milk (including: Cederberg and Mattsson, 2000; Basset-Mens et al., 2005; Saunders and Barber, 2007). Yan et al. (2011) noted that economic allocation has been employed for the majority of previous LCA of European milk production. This method is, however, dependent on stable prices. Thus in view of the volatility in UK milk prices both at present and over the study period, even when considering price as a rolling average, economic allocation was deemed unsuitable for this LCA. O'Brien et al (2010) allocated emissions to co-products based on biological causality, whereby only the emissions produced by lactating cows were allocated to milk. Under this method, emissions produced by young stock and by pregnant dry cows were allocated to meat. The International Dairy Federation (IDF) state that a physical allocation based on mass of milk and meat is most appropriate (IDF, 2010), with a default value of 85.6% allocated to milk. Kristensen et al. (2011) noted after reviewing all of the above allocation methods that, for systems with only two products, the use of either mass or biological methods seems more appropriate.

The present study therefore employed the IDF (2010) method of mass allocation between milk and the liveweight of animals sold. A system specific allocation value was determined for each year of the study, to be used in the LCA model. The average allocation value to milk solids was 83%, 88%, 81%, 87% for LFC, LFS, HFC, HFS respectively.

#### 3.2.3.4 Impact category

The impact category for the present study was global warming potential, expressed in units of kilograms of carbon dioxide equivalents (kgCO<sub>2</sub>e).

#### 3.2.4 Inventory Analysis

The inventory analysis phase of the LCA was conducted, in order to collect and quantify the data concerning resource use, energy consumption, and emissions resulting from each activity in the production system (Thomassen et al., 2008b).

##### 3.2.4.1 Emissions derived from livestock

Emissions of CH<sub>4</sub> were calculated for enteric fermentation and storage of animal manures. Enteric CH<sub>4</sub> was estimated using the non-linear equation by Mills et al. (2003) based upon metabolisable energy intake (MEI), and presented below as Equation 3.2. A previous study (Bell et al., 2009) concluded that this was the most suitable equation for predicting enteric CH<sub>4</sub> emissions from the Langhill herd. The merit of the equation by Mills et al. (2003) is enhanced by adoption of biologically sensible constraints; that there are zero CH<sub>4</sub> emissions at zero feed intake, and an upper limit imposed on the production of CH<sub>4</sub> by one cow. The non-linear equation follows the form  $y = a - (a + b)e^{-cx}$  where:  $y$  is the daily enteric CH<sub>4</sub> produced per cow;  $a$  and  $b$  are the maximum and minimum values of  $y$  respectively,  $c$  is a constant, and  $x$  is the input variable MEI.

**Equation 3.2** Enteric CH<sub>4</sub> (MJ day<sup>-1</sup>) = 45.98 - (45.98 + 0.00)e<sup>-0.003 x MEI</sup>

Methane from manure management and field deposition was calculated using Equation 3.3 (IPCC, 2006). This enabled use of system specific emissions factors accounting for the different categories of management and storage of manures, and the proportion of annual manure managed in each.

**Equation 3.3**  $EF_{(L)} = (VS_{(L)} * 365) * [B_{0(L)} * 0.67 \text{kg m}^{-3} * \sum_{S,k} \frac{MCF_{(S,k)}}{100} * MS_{(L,S,k)}]$

Where:  $EF_{(L)}$  = annual manure CH<sub>4</sub> emission factor for livestock category  $L$ , kg CH<sub>4</sub> cow<sup>-1</sup> yr<sup>-1</sup>;  $VS_{(L)}$  = daily volatile solid excreted for livestock category  $L$ , kgDM cow<sup>-1</sup> day<sup>-1</sup>;  $B_{0(L)}$  = maximum methane producing capacity for manure produced by

livestock category  $L$ ,  $0.24\text{m}^3 \text{CH}_4 \text{kg}^{-1}$  of VS excreted;  $0.67$  = conversion factor of  $\text{m}^3 \text{CH}_4$  to  $\text{kg CH}_4$ ;  $\text{MCF}_{(S,k)}$  = methane conversion factors for each manure management system  $S$  in climate region  $k$ , given as 1% for pasture, 2% for solid storage and 17% for liquid storage without natural crust cover;  $\text{MS}_{(T,S,k)}$  = fraction of livestock category manure handled using manure management system  $S$ , dimensionless; Average annual temperature  $T$  over the period at CRF was  $10^\circ\text{C}$ .

Pereira et al. (2011) noted a higher rate of ammonia emissions from manures deposited on a scraped solid floor compared to slatted floor in cattle housing before storage in liquid system. Both solid and slatted floors were present in the Langhill cows' housing but this study did not account for difference between them. Based on the proportion of the year spent in the main housing unit, LF group cows were estimated to have deposited approximately 83% of their manure into liquid management system. The remaining 17% was managed in a solid manure system, reflecting the period of time LF cows spent in dry and transition periods. Storage of manures from HF groups was more variable owing to availability of grazing each year; manure in liquid storage ranged from 51% to 60% over the study period, while deposition at pasture ranged from 23% to 32%. Solid manure storage was again approximately 17% for HF cows managed when dry or in transition. Manure from young stock and heifers was assumed to be managed 100% in solid storage as they were fully housed prior to transition period before first calving.

Excreted nitrogen was determined as the difference between nitrogen consumed and nitrogen utilised in production, growth and maintenance. Nitrogen consumed was estimated from weekly averages of cows' dry matter intake (DMI) and weekly feed samples to determine crude protein (CP) content of their diet. System specific excreted nitrogen coefficients ( $\text{kg N cow}^{-1}\text{year}^{-1}$ ) were estimated for each livestock category in the herd dynamics model for each year of the study period. Emissions of  $\text{N}_2\text{O}$  derived from manures were calculated according to the IPCC methods (IPCC, 2006). Direct livestock derived emissions arose from manure management and deposition at pasture. Indirect  $\text{N}_2\text{O}$  emissions from volatilisation, leaching and run-off from manure management, deposition at pasture and the application of slurry/manure to crops were included in the calculations. The specific emissions factors employed in calculations for this study are presented in Table 3.3.

**Table 3.3: Emissions factors with default values, uncertainty parameters and probabilistic distributions applied for sensitivity analysis**

Factor	Description	Units	Default	Range	Distribution
EF <sub>1</sub>	<sup>a</sup> Direct from applied fertiliser to soil	kgN <sub>2</sub> O-N kgN <sup>-1</sup>	0.01	0.003-0.03	Beta
EF <sub>4</sub>	<sup>a</sup> Volatilisation, atmospheric deposition of nitrogen	kgN <sub>2</sub> O-N kgN <sup>-1</sup>	0.01	0.002-0.05	Beta
EF <sub>5</sub>	<sup>a</sup> Leaching and run-off	kgN <sub>2</sub> O-N kgN <sup>-1</sup>	0.0075	0.0005-0.025	Beta
Frac <sub>LEACH</sub>	<sup>a</sup> % lost from leaching	%	30	10-80	Beta
EF <sub>3 PRP</sub>	<sup>a</sup> Direct from deposition of cows' excreta at pasture	kgN <sub>2</sub> O-N kgN <sup>-1</sup>	0.02	0.007-0.06	Beta
Frac <sub>GASM</sub>	<sup>a</sup> Volatilisation from animal excreta at pasture	%	20	5-50	Beta
EF <sub>3 SS</sub>	<sup>a</sup> Direct from solid storage of animal manure	kgN <sub>2</sub> O-N kgN <sup>-1</sup>	0.005	0.0025-0.01	Beta
Frac <sub>SSV</sub>	<sup>a</sup> Volatilisation from solid storage of animal manure	%	30	10-40	Beta
EF <sub>3 LS</sub>	<sup>a</sup> Direct from liquid storage of animal manure	kgN <sub>2</sub> O-N kgN <sup>-1</sup>	0	0	-
Frac <sub>LSV</sub>	<sup>a</sup> Volatilisation from liquid storage of animal manure	%	40	15-45	Beta
EF <sub>1CR</sub>	<sup>a</sup> Direct from crop residues	kgN <sub>2</sub> O-N kgN <sup>-1</sup>	0.01	0.003-0.03	Beta
EF <sub>urea</sub>	<sup>a</sup> Direct emissions from applied urea	kgCO <sub>2</sub> -C kgUrea <sup>-1</sup>	0.2	0.0-0.2	Triangular
EF <sub>Nex</sub>	<sup>b</sup> Excreted Nitrogen	kgN cow <sup>-1</sup> year <sup>-1</sup>	Specific to system and age		Normal
EF <sub>ent</sub>	<sup>b</sup> Enteric methane	kgCH <sub>4</sub> cow <sup>-1</sup> year <sup>-1</sup>	Specific to system and age		Normal
EF <sub>man</sub>	<sup>b</sup> Manure methane	kgCH <sub>4</sub> cow <sup>-1</sup> year <sup>-1</sup>	Specific to system and age		Normal
EF <sub>N</sub>	<sup>c</sup> Production of nitrogen	kgCO <sub>2</sub> e kgN <sup>-1</sup>	7.11	6.85-7.37	Beta
EF <sub>P</sub>	<sup>c</sup> Production of phosphate	kgCO <sub>2</sub> e kgP <sup>-1</sup>	1.85	1.61-2.09	Beta
EF <sub>K</sub>	<sup>c</sup> Production of potash	kgCO <sub>2</sub> e kgK <sup>-1</sup>	1.76	1.61-1.91	Beta
EF <sub>diesel</sub>	<sup>d</sup> Associated with red diesel	kgCO <sub>2</sub> e l <sup>-1</sup>	3.176	2.818-3.533	Beta
EF <sub>petrol</sub>	<sup>d</sup> Associated with petrol	kgCO <sub>2</sub> e l <sup>-1</sup>	2.667	2.368-3.065	Beta
EF <sub>elec</sub>	<sup>d</sup> Associated with electricity	kgCO <sub>2</sub> e kWh <sup>-1</sup>	0.594	0.582-0.605	Normal

Emissions factors and range sourced from: <sup>a</sup>IPCC (2006), <sup>b</sup>System specific calculations, <sup>c</sup>Carbon Trust (2010b)/NEA (2010), <sup>d</sup>DEFRA (2011a). Distributions applied to the range of emissions factors are pertinent to the sensitivity analysis.

### 3.2.4.2 Emissions derived from manufactured fertilisers

Emissions of N<sub>2</sub>O and CO<sub>2</sub> were estimated according to IPCC (2006) methods. Direct N<sub>2</sub>O emissions were determined for the application of all fertilisers to the soil. Indirect emissions were determined for volatilised fertiliser nitrogen, leaching and run-off. Direct emissions of CO<sub>2</sub> arising from applied urea were also determined. In addition, factors used for emissions associated with the production and delivery of

manufactured fertilisers were taken to be 7.11, 1.85 and 1.76 kg CO<sub>2</sub>e tonne<sup>-1</sup> of nitrogen, phosphate and potash respectively (Carbon Trust, 2010b).

#### *3.2.4.3 Emissions derived from crops*

Emissions of N<sub>2</sub>O from crop residues were estimated according to IPCC (2006) methods. Estimates of emissions accounted for direct emissions from crop residues and indirect emissions from volatilisation, leaching and run-off. Emissions associated with alkaline treatment process of wheat alkalage were not included.

#### *3.2.4.4 Emissions derived from energy use*

Emissions of carbon dioxide equivalents (CO<sub>2</sub>e) from electricity and fossil fuel use were calculated using the scope 3 emissions factors sourced from the most recent published DEFRA GHG Conversion Factors for Company Reporting. Emissions factors employed for the production, delivery and use of energy were taken to be 0.594 kg CO<sub>2</sub>e kWh<sup>-1</sup> for electricity and 3.176 kg CO<sub>2</sub>e l<sup>-1</sup> for red diesel respectively (DEFRA, 2011a).

#### *3.2.4.5 Emissions derived from purchased feeds*

Embedded emissions of CO<sub>2</sub>e associated with the production and delivery of purchased feeds were determined using emissions factors sourced from the Carbon Trust Food Database v1.1 and the Carbon Trust Crop Calculator v3.1 (Carbon Trust, 2010a; 2010b). As a substantial proportion of the purchased blend in both the HF and LF cows' diet was sourced from distillery by-products, the emissions factors for the purchased feeds were considerably lower than if grain had been directly produced for animal feed. Allocations were made between co-products where they existed for some imported concentrates, for example between rapeseed oil and rapeseed meal. Allocations of this type were made according to the allocation values of Cederberg and Mattsson (2000), which were similarly employed by Bell et al. (2011).



Allocations of embedded CO<sub>2</sub>e were made as follows for purchased feed components:

- sugar beet - 66% sugar, 22% beet pulp, 12% molasses.
- soya (not accounting for land use change) – 20% oil, 80% meal
- rapeseed – 40% oil, 60% meal

### 3.2.5 Impact Assessment

Environmental impact assessment was conducted using a modified version of the PAS2050 accredited SAC Carbon Calculator vII (RBU, 2011), designed specifically for use in the Scottish agricultural sector and implementing IPCC Tier 2 methods (IPCC, 2006). Liaising closely with the developer, this study was able to implement system specific values for enteric methane and excreted nitrogen coefficients, as well as calculator inputs such as productivity and feed intake, digestibility and crude protein content. In this way specific differences amongst the four dairy production systems may be properly defined.

Emissions of kg CO<sub>2</sub>e for major GHG were calculated using conversion factors for a 100 year time horizon. These factors were defined to be 25 and 298 for CH<sub>4</sub> and N<sub>2</sub>O respectively (IPCC, 2007a). The total GWP was calculated for each of the four Langhill systems - LFC, LFS, HFC and HFS – for each of seven full calendar years of the study period. In addition, the contribution to the overall GWP associated with the following sources was calculated: enteric fermentation, CH<sub>4</sub> from manures, N<sub>2</sub>O from manures, production of manufactured fertilisers, application of manufactured fertilisers, purchased feed & bedding, crop residues, fossil fuels and electricity. The most efficient system was determined as having the lowest GWP per FU.

### 3.2.6 Statistical Analysis

The effect of dairy production system upon the GWP was assessed using analysis of variance (ANOVA) employing a general linear model (GLM) procedure. The four dairy production systems were representative of the interaction between forage regime and genetic line. Dairy production systems were also broken down further in

the model in order to examine the individual effects of forage regime and genetic line upon GWP. The GLM used was:

$$y_{ij} = \mu + F_i + G_j + (FxG)_{ij} + Y_{ij} + \varepsilon_{ij}$$

where  $y_{ij}$  is the global warming potential expressed per kg ECM;  $\mu$  is the overall mean;  $F_i$  is the fixed effect of feeding regime (Low forage or High forage);  $G_j$  is the fixed effect of genetic line (Control or Select);  $(FxG)_{ij}$  is the effect of production system (LFC, LFS, HFC, HFS);  $Y_{ij}$  is the random effect of calendar year (2004-2010);  $\varepsilon_{ij}$  is the random error term. Significant differences between variables were determined by conducting pairwise comparisons using the Tukey method. All statistical analysis was conducted using Minitab 16.

### 3.2.7 Sensitivity Analysis

The SAC Carbon Calculator employed in this study was a deterministic model, producing a single figure representing the GWP of an agricultural production system for an annual period. There is, however, a degree of uncertainty in the literature sourced emissions factors employed in impact assessment and in the calculated system specific emissions factors, as well as variation in the farm-derived input data. It was therefore necessary to perform a stochastic simulation analysis in order to assess the effect of this uncertainty upon the results of the LCA. This sensitivity analysis was also able to determine which emissions sources, and which specific emissions factors within those sources, were contributing the largest uncertainty to the estimated GWP. This study thus conducted sensitivity analysis of the uncertainties associated with input variables, as opposed to the variables themselves.

The method of analysis was similar to that of a previous LCA study in New Zealand (Basset Mens et al., 2009b), employing the @Risk package (Palisade Corporation, 2012) to perform Monte Carlo simulations. Probabilistic distributions for inventory emissions factors were applied based on the uncertainty parameters specified in the literature (IPCC, 2006; Carbon Trust, 2010b; DEFRA, 2011a). In the absence of information about the shape of the parameters' distribution, a beta-pert distribution was applied, as demonstrated by Brown et al. (2001). As the parameter range above a

given default value was often less than the range below it, employing this distribution preserved any asymmetry (Gibbons et al., 2006), with a specified maximum, minimum and most likely value. The system-specific Tier 3 emissions factors estimated for enteric CH<sub>4</sub>, manure CH<sub>4</sub> and animal excreted nitrogen were normally distributed. The uncertainty parameters and distributions applied to emissions factors were those that are presented in Table 3.3. Employing sensitivity analysis such as Monte Carlo simulations assumes independence amongst input variables, and this approach was deemed appropriate to deal with the emissions factors and coefficients in the model. However, the dynamic nature of dairy production systems entails that many of farm-derived input data are inherently interdependent. Sets of synthetic farm input data were generated for each system by multilinear regression, employing DMI per cow and the number of LU as key variables, as defined by Basset-Mens et al. (2009b). The synthetic farm input data were representative of the range of dependent input variables for each of the four dairy production systems over the period. With each iteration of Monte Carlo simulation, farm-derived data were thus treated by sensitivity analysis as dependent variables where appropriate.

Monte Carlo simulations were performed for each of the Langhill systems, with each model run consisting of 10,000 iterations. The resulting distributions for the GWP thus take account of the uncertainty in both the farm derived input data and the emissions factors employed in calculations. Output data generated by Monte Carlo simulations for the overall GWP was then assessed by way of ANOVA to determine significant differences between dairy production systems. Analysis employed the same GLM as before, with the year term removed. The Monte Carlo procedure also calculated regression coefficients in order to explain how much of the observed uncertainty in the resulting distributions could be attributed to the uncertainty associated with each contributing emissions source. In the sensitivity analysis output from @Risk, a normalised multiple regression coefficient of 0 indicates no relationship between the input and output, while a value of 1 or -1 indicates a 1 or -1 standard deviation change in the output for a 1 standard deviation change in the input. Within each contributing source, regression coefficients were also determined for the parameters listed in Table 3.3, employed in the impact assessment calculations for each production system.

### 3.3 Results

This section deals with the results of analysis in three parts. Firstly the results obtained directly from the deterministic LCA model, secondly the output and significant results obtained from ANOVA assessing the effect of dairy production system on GWP, and thirdly the results of sensitivity analysis.

#### 3.3.1 Life Cycle Output

A breakdown of LCA outputs, including: the contribution of each gross component GHG to the GWP per kgECM; average on-farm, off-farm and total land requirements per kgECM; and average annual milk yield per cow, is presented in Table 3.4.

**Table 3.4: Descriptive statistics for gross Life Cycle Assessment (LCA) outputs**

Output	Units	Production system							
		LFC		LFS		HFC		HFS	
		mean	sd	mean	sd	mean	sd	mean	sd
CO <sub>2</sub> (on-farm)	kgCO <sub>2</sub> e kg <sup>-1</sup> ECM	0.07	0.01	0.07	0.01	0.07	0.01	0.07	0.01
CO <sub>2</sub> e (off-farm)	kgCO <sub>2</sub> e kg <sup>-1</sup> ECM	0.20	0.01	0.19	0.01	0.20	0.03	0.19	0.03
CH <sub>4</sub>	kgCO <sub>2</sub> e kg <sup>-1</sup> ECM	0.50	0.04	0.44	0.04	0.59	0.02	0.54	0.05
N <sub>2</sub> O	kgCO <sub>2</sub> e kg <sup>-1</sup> ECM	0.14	0.01	0.13	0.01	0.23	0.01	0.21	0.02
Total GWP	kgCO <sub>2</sub> e kg <sup>-1</sup> ECM	0.92	0.06	0.83	0.05	1.10	0.06	1.00	0.08
Milk yield	kgECM cow <sup>-1</sup> yr <sup>-1</sup>	9246	800	10753	853	7281	533	8189	656
On-farm land	m <sup>2</sup> kg <sup>-1</sup> ECM yr <sup>-1</sup>	0.59	0.07	0.53	0.07	0.98	0.16	0.88	0.13
Off-farm land	m <sup>2</sup> kg <sup>-1</sup> ECM yr <sup>-1</sup>	0.90	0.09	0.80	0.09	0.42	0.06	0.33	0.04
Total land	m <sup>2</sup> kg <sup>-1</sup> ECM yr <sup>-1</sup>	1.49	0.14	1.33	0.14	1.40	0.22	1.21	0.16

Where: LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select; and CO<sub>2</sub> = carbon dioxide, CO<sub>2</sub>e = carbon dioxide equivalents, CH<sub>4</sub> = methane, N<sub>2</sub>O = nitrous oxide, GWP = global warming potential, m<sup>2</sup> = square metres, yr = year; and ECM = energy corrected milk

##### 3.3.1.1 Greenhouse gas emissions

Methane made the highest contribution to the overall GWP, comprising around 50-57% of the total in all systems. On-farm CO<sub>2</sub> emissions made the lowest contribution for all systems. In the two HF groups, emissions of N<sub>2</sub>O (21%) contributed more to the overall GWP than the indirect CO<sub>2</sub>e (18-19%) associated with off-farm processes. Off-farm emissions include those embedded in production and delivery of purchased feed, bedding, and manufactured fertilisers. Conversely, for the two LF

groups, contribution from off-farm CO<sub>2</sub>e (22-23%) was greater than that from N<sub>2</sub>O (15-16%).

### *3.3.1.2 Productivity*

Average annual milk yield per cow was observed to be 10753 kg per cow in LFS, around 48% higher than in HFC, representing an average difference of over 3000 kg per cow between the systems. Productivity was therefore a key factor in this study.

### *3.3.1.3 Land use*

On-farm land use per kg ECM was greater for the HF groups, with HFC requiring the most farm land (0.98 m<sup>2</sup> kg<sup>-1</sup>ECM) and LFS the least (0.53 m<sup>2</sup> kg<sup>-1</sup>ECM). However, off-farm land was greater in LF groups, with LFC estimated to require the highest (0.90 m<sup>2</sup> kg<sup>-1</sup>ECM). Low forage groups were estimated to require 55-58% more land off-farm than on-farm. Conversely, High forage groups required 39-43% less land off-farm than on-farm. Total combined land use, incorporating land used for forages, grazing (where appropriate) and production of purchased feeds was greater in LF groups. LFC was estimated to require the highest total land use (1.49 m<sup>2</sup> kg<sup>-1</sup>ECM) to produce 1kg ECM, followed by HFC, LFS and HFS (1.40, 1.33 and 1.21 m<sup>2</sup> kg<sup>-1</sup>ECM respectively).

## **3.3.2 Effect of Production System**

### *3.3.2.1 Total overall global warming potential*

The effect of the production system on the total overall GWP was found to be highly significant ( $P < 0.001$ ). The most GHG efficient system was defined as having the lowest emissions intensity, i.e. lowest GWP per unit ECM. Thus over the study period, the LFS was found to be the most GHG efficient system (least squares mean = 0.83 kg CO<sub>2</sub>e kg<sup>-1</sup>ECM, standard error of the mean = 0.016). The HFC system was found to have the highest emissions intensity (1.10 kg CO<sub>2</sub>e kg<sup>-1</sup> ECM). The GWP per unit milk of LFS was therefore around 24% lower than that of HFC, and all four production systems were found to be significantly different ( $P < 0.001$ ) from each other. A breakdown of results from ANOVA, showing the effect production system upon the GWP of contributing sources, is presented in Table 3.5.

**Table 3.5: Breakdown of results from Analysis of Variance (ANOVA), showing the effect of interaction of forage regime and genetic line upon Global Warming Potential (GWP) per kilogram energy corrected milk (ECM), attributed to contributing categories of Life Cycle Analysis**

Variable	Level	Fossil fuels CO <sub>2</sub>	Electricity CO <sub>2</sub>	Manufactured fertiliser production CO <sub>2</sub> e	Purchased feed & bedding CO <sub>2</sub> e	Enteric fermentation CH <sub>4</sub>	Animal manure CH <sub>4</sub>	Animal manure N <sub>2</sub> O	Manufactured fertiliser application N <sub>2</sub> O	Crop residues N <sub>2</sub> O	Total Overall GWP CO <sub>2</sub> e
Production system (FxG)	LFC	0.051 <sup>a</sup>	0.022	0.048	0.154 <sup>a</sup>	0.451 <sup>a</sup>	0.052	0.078 <sup>a</sup>	0.036	0.030	0.921 <sup>a</sup>
	LFS	0.048 <sup>b</sup>	0.024	0.045	0.143 <sup>b</sup>	0.393 <sup>b</sup>	0.049	0.067 <sup>b</sup>	0.034	0.028	0.830 <sup>b</sup>
	HFC	0.048 <sup>b</sup>	0.025	0.074	0.129 <sup>c</sup>	0.518 <sup>c</sup>	0.074	0.129 <sup>c</sup>	0.056	0.044	1.096 <sup>c</sup>
	HFS	0.046 <sup>c</sup>	0.026	0.071	0.118 <sup>d</sup>	0.462 <sup>a</sup>	0.073	0.113 <sup>d</sup>	0.053	0.042	1.005 <sup>d</sup>
	sem	0.0008	0.0008	0.0032	0.0030	0.0094	0.0027	0.0029	0.0024	0.0005	0.0163
Forage regime (F)	Low (LF)	0.049 <sup>a</sup>	0.023 <sup>a</sup>	0.046 <sup>a</sup>	0.149 <sup>a</sup>	0.422 <sup>a</sup>	0.051 <sup>a</sup>	0.073 <sup>a</sup>	0.035 <sup>a</sup>	0.029 <sup>a</sup>	0.876 <sup>a</sup>
	High (HF)	0.047 <sup>b</sup>	0.026 <sup>b</sup>	0.073 <sup>b</sup>	0.124 <sup>b</sup>	0.490 <sup>b</sup>	0.073 <sup>b</sup>	0.121 <sup>b</sup>	0.055 <sup>b</sup>	0.043 <sup>b</sup>	1.051 <sup>b</sup>
	sem	0.0006	0.0005	0.0027	0.0020	0.0067	0.0019	0.0020	0.0017	0.0004	0.0116
Genetic line (G)	Control (C)	0.049 <sup>a</sup>	0.024	0.061	0.142 <sup>a</sup>	0.484 <sup>a</sup>	0.063	0.103 <sup>a</sup>	0.046	0.037 <sup>a</sup>	1.009 <sup>a</sup>
	Select (S)	0.047 <sup>b</sup>	0.025	0.058	0.131 <sup>b</sup>	0.428 <sup>b</sup>	0.061	0.090 <sup>b</sup>	0.043	0.035 <sup>b</sup>	0.918 <sup>b</sup>
	sem	0.0006	0.0005	0.0027	0.0020	0.0067	0.0019	0.0020	0.0017	0.0004	0.0116

All results presented as least squares means (lsm) with standard errors of the mean (sem), and expressed in terms of kilograms of carbon dioxide equivalents per kilogram Energy Corrected Milk (kg CO<sub>2</sub>e kg ECM<sup>-1</sup>). Different superscripts within a column denote significant differences between levels of same variables (P<0.001). Where: LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select; and CO<sub>2</sub> = carbon dioxide, CO<sub>2</sub>e = carbon dioxide equivalents, CH<sub>4</sub> = methane, N<sub>2</sub>O = nitrous oxide, GWP = global warming potential.

Within a forage regime, the Select line had lower overall GWP than Control ( $P<0.001$ ). Using ECM as a functional unit, the overall GWP was observed to be 17% lower in Low forage regime and 9% lower in the Select line ( $P<0.001$ ).

#### *3.3.2.2 Breakdown of contributing LCA emissions sources*

The effect of production system was significant ( $P<0.001$ ) for the GWP associated with fossil fuel use, purchased feed and bedding, enteric methane, and  $N_2O$  emissions from animal manures. HFS had the lowest GWP per unit milk associated with fuel use and LFC the highest, while LFS and HFC were not significantly different. Individually, fossil fuel GWP was 6% higher in Low forage regime and 6% higher in the Control line. In terms of the emissions embedded in purchased feed and bedding, HFS was again the most efficient, with GWP 24% lower than the least efficient LFC. Within a forage regime the Select line was 8% lower than Control with respect to purchased feed and bedding, and High forage was 17% lower than Low forage.

Global warming potential associated with enteric fermentation was lowest in LFS ( $0.39 \text{ kg CO}_2\text{e kg ECM}^{-1}$ ) and 32% higher in HFC ( $0.52 \text{ kg CO}_2\text{e kg ECM}^{-1}$ ). The individual effect upon GWP of the Low forage regime and Select genetic line were 16% and 12% lower respectively in terms of enteric  $CH_4$ . LFS was found to be the most efficient system ( $0.07 \text{ kg CO}_2\text{e kg ECM}^{-1}$ ) in terms of  $N_2O$  emissions from deposition and management of manures. Conversely, HFC produced 91% more  $N_2O$  from animal manures compared with LFS. Emissions of  $N_2O$  from animal manures were around 40% lower in High forage regime than Low forage, and 13% lower in Select line.

#### *3.3.2.3 Individual effects of forage regime and genetic line*

The effect of production system was not found to be significant upon the GWP associated with electricity use or methane from animal manures. Neither was the term significant for embedded emissions in production of manufactured fertilisers,  $N_2O$  emissions from applied manufactured fertilisers, or from crop residues. In all

five cases the individual effect of forage regime was significant ( $P < 0.001$ ). The Low forage regime was found to be more efficient than High forage in each of the five categories. Amongst these categories, the individual effect of genetic line was only found to be significant for  $N_2O$  emissions from crop residues, where Select was estimated to have around 5% lower GWP than Control.

Around 88% of the total  $CH_4$  produced was attributed to enteric fermentation, and this proportion was consistent across all systems. Off-farm emissions associated with purchased feed and bedding made the second highest contribution to GWP of the Low forage regime (16-20%), around double the contribution of  $N_2O$  from management of animal manures (7-9%). In the systems managed under High forage regime, the embedded  $CO_2e$  emissions in feed and bedding were comparable with those  $N_2O$  emissions associated with management of animal manures and deposition at pasture (10-13%). All emissions associated with manufactured fertiliser were higher in High forage regime.

### 3.3.3 Sensitivity Analysis

#### 3.3.3.1 Uncertainty in overall global warming potential

The data populations generated by Monte Carlo analysis produced a distribution of results for the GWP of each system, owing to the variation in emissions factors and farm-derived data. The mean values, confidence intervals and coefficients of variation of the data populations for each dairy production system, are presented in Table 3.6.

**Table 3.6: Mean values, lower and upper confidence intervals, and coefficients of variation (CV) for dairy production systems, generated by Monte Carlo simulation**

Production System	GWP kg $CO_2e$ kgECM <sup>-1</sup>	Confidence Interval		CV %
		Lower (2.5%) kg $CO_2e$ kgECM <sup>-1</sup>	Upper (97.5%) kg $CO_2e$ kgECM <sup>-1</sup>	
LFC	0.97 <sup>a</sup>	0.88	1.06	5.26
LFS	0.87 <sup>b</sup>	0.79	0.94	5.26
HFC	1.15 <sup>c</sup>	1.04	1.27	5.89
HFS	1.06 <sup>d</sup>	0.95	1.17	5.88
sem	0.001			

Different superscripts within a column denote significant differences between levels of same variables ( $P < 0.001$ )



Mean values of the generated populations were around 5% higher than the mean overall GWP obtained from the LCA. This owed to the use of asymmetric beta distributions applied to IPCC emissions factors, with a higher probability observed above the specified likely value. After accounting for the variation introduced by both the uncertainty in farm-derived input data and the uncertainty in coefficients and emissions factors, the four dairy production systems were found to be all significantly different ( $P < 0.001$ ) from each other in terms of their overall GWP. There was higher variation in the two High forage systems (coefficient of variation (CV) = 5.9%) than Low forage systems (CV = 5.3%).

#### *3.3.3.2 LCA emissions sources contributing to uncertainty*

Nitrous oxide emissions associated with the deposition and management of animal manures was found to be the source contributing the largest amount of variation in the overall GWP due to uncertainty in the emissions factors. This was consistent across all four dairy production systems. The regression coefficients for this category variable were considerably higher than those determined for the uncertainty due to variation in enteric  $\text{CH}_4$  coefficients. Uncertainty in the emissions factors for enteric fermentation was found to contribute the second highest amount of variation to the overall GWP of all four systems. In both LFC and LFS, the coefficient for  $\text{CH}_4$  from animal manures was the 3<sup>rd</sup> highest contributor of uncertainty, followed by the category for  $\text{N}_2\text{O}$  associated with applied manufactured fertilisers, and then crop residues. Estimated nitrous oxide emissions from manufactured fertilisers contributed the 3<sup>rd</sup> largest amount of uncertainty to the total GWP of both HFC and HFS. The regression coefficients determined for the defined component LCA categories contributing to the overall GWP are presented in Table 3.7.

**Table 3.7: Regression coefficients explaining contribution of variation in each LCA output category to uncertainty in estimated overall global warming potential (GWP)**

Contributing category variable	Production System							
	LFC		LFS		HFC		HFS	
	Rank	Coeff	Rank	Coeff	Rank	Coeff	Rank	Coeff
N <sub>2</sub> O animal manures	1	0.760	1	0.737	1	0.728	1	0.727
CH <sub>4</sub> enteric fermentation	2	0.435	2	0.444	2	0.443	2	0.430
CH <sub>4</sub> animal manures	3	0.322	3	0.352	5	0.279	4	0.306
N <sub>2</sub> O purchased fertiliser application	4	0.271	4	0.280	3	0.341	3	0.347
N <sub>2</sub> O crop residues	5	0.240	5	0.250	4	0.287	5	0.292
CO <sub>2</sub> e fossil fuels	6	0.049	6	0.051	6	0.036	6	0.037
CO <sub>2</sub> e purchased fertiliser production	7	0.014	7	0.014	7	0.015	7	0.014
CO <sub>2</sub> e electricity	8	0.008	8	0.010	8	0.007	8	0.008

### 3.3.3.3 Key emissions factors contributing to uncertainty

Six key emissions factors were identified as contributing the most to the observed uncertainty in overall GWP:

- i. IPCC coefficient for indirect emissions from volatilised nitrogen (EF<sub>4</sub>)
- ii. System-specific coefficients for excreted nitrogen rates
- iii. System-specific coefficients for CH<sub>4</sub> from enteric fermentation
- iv. System-specific coefficients for CH<sub>4</sub> from manure management
- v. IPCC coefficient for emissions from animals' deposition at pasture (EF<sub>3 PRP</sub>)  
(for systems managed under High forage regime only)
- vi. IPCC coefficient for direct N<sub>2</sub>O emissions (EF<sub>1</sub>) from applied fertilisers

In all four dairy production systems, the greatest contribution to uncertainty was found to arise from EF<sub>4</sub>, concerning indirect emissions from the volatilisation of nitrogen. This coefficient was the dominant factor contributing uncertainty in N<sub>2</sub>O emissions from deposition and management of animal manures. The system-specific Tier 3 emissions factors for excreted nitrogen, CH<sub>4</sub> from enteric fermentation, and CH<sub>4</sub> from manure management were found to contribute the second, third and fourth highest amounts of variation respectively. The IPCC coefficient for direct N<sub>2</sub>O emissions (EF<sub>1</sub>) was the dominant parameter in contributing to the uncertainty in GWP from applied manufactured fertilisers and also from crop residues. In two systems (HFC and HFS), the factor for N<sub>2</sub>O emissions from excreta deposited on

pasture by grazing animals ( $EF_3_{PRP}$ ) was also found to contribute a large amount of the uncertainty within the  $N_2O$  from animal manures category. The influence of this emissions factor was not applicable to the two Low forage systems.

### 3.4 Discussion

#### 3.4.1 Life Cycle Impact Assessment

##### *3.4.1.1 Environmental efficiency of production systems*

The four dairy production systems in this study examine contrasting approaches to dairy herd management, and are representative of a range of conventional dairy systems possible in Scotland. The results for the estimated GWP of the four Langhill systems are broadly in line with figures found in the literature for a conventional European dairy production system (Cederberg and Mattson, 2000; Cederberg and Flysjö, 2004; Haas et al., 2001; van der Werf et al., 2009). All four Langhill systems were estimated to have a lower GWP than the British average, estimated to be  $1.31 \text{ kg CO}_2\text{e kg}^{-1}\text{ECM}$  in the recent national study covering 415 dairy farms (DairyCo, 2012a). This is likely due in part to the higher than average productivity of the Langhill herd, as well as a lower than average use of manufactured fertilisers permitted through the practicing of more efficient use of organic fertilisers. Farms in the national study will have employed a range of different feeding regimes, diets, sources of feeds and animal management into later lactations. Further, the DairyCo study calculations used national data sources, allocation techniques and emissions factors compliant with PAS:2050.

Basset-Mens (2008) noted that the strength of drawing direct comparisons between the results of different studies at dairy systems level has in the past been questionable. As the four systems were managed within the boundaries of the same farm, the LCA results from the present study can be confidently directly compared to each other. These results suggest that there is potential to reduce the GWP per unit productivity of a typical conventional UK dairy system by up to 24%. The individual significance of effect of genetic line suggests that improving the genetic merit of a dairy herd could potentially bring around 9% reduction in the GWP per unit productivity.

Improvement of this nature necessarily proceeds gradually through breeding and would realistically take several years to return results. Once established, however, in the Langhill herd the higher genetic merit delivered an increase of around an 18% in milk yield and contributed significantly to lowering overall GWP. Similarly, the individual significance of forage regime suggests that switching to the Low forage regime holds potential for a reduction in GWP of up to 17% per unit productivity. These results in the present study agree with the findings of previous studies (Garnsworthy et al., 2005; Casey and Holden, 2005b; Bell et al., 2009), who found that improving the productivity of the herd would significantly reduce enteric CH<sub>4</sub> emissions and overall GWP per unit milk. Furthermore, the results of this study confirm that implementing the Low forage regime reduced GWP per kg milk irrespective of cows' genetic merit. However, implementing a Low forage ration comprising a different ratio or combination of purchased feed components could change the scale of potential GWP reductions identified. This could comprise a higher inclusion of soy or rapeseed meal where by-products are unavailable.

#### *3.4.1.2 Balance of enteric methane versus lost nitrogen*

The key to reducing the overall GWP at systems level, however, lies in understanding where trade-offs arise in the dynamic nature of GHG production in dairy systems. By focussing analysis on just one or selected parts of a dairy farm system, striving towards efficiency in a particular aspect within that system, such as animal welfare or productivity, may influence emissions in another and thus may negatively influence the environmental efficiency of the system as a whole. Chagunda et al. (2009) showed that although increasing milk production was associated with a reduction in enteric CH<sub>4</sub> per unit milk, excreted nitrogen could consequently increase, and thus also increase the emissions from animal manures. Gross enteric CH<sub>4</sub> production was higher per cow in Low forage regime, owing to the higher metabolisable energy (ME) content of the Low forage ration. Similarly, total enteric CH<sub>4</sub> was greater in the high genetic merit groups, attributed to higher DMI (and thus higher MEI as well) associated with the Select genetic line. When referenced to productivity, however, the GWP from enteric CH<sub>4</sub> in Select groups was lower than Control, and the Low forage regime less than High forage per unit milk. High gross enteric CH<sub>4</sub> was therefore being offset by the greater milk yield

associated with Select genetic line and Low forage diet. These results are consistent with the findings of Chagunda et al. (2009) and Bell et al. (2010). A potential trade-off with this high level of productivity was noted earlier to be an increase in excreted nitrogen losses. The results of this study show, however, that GWP from deposition and management of animal manures was actually lowest per unit productivity for the highest yielding system. The HFC system was found to produce 91% more N<sub>2</sub>O per kg ECM from animal manures compared with LFS, a difference which cannot be attributed to LFS emissions being offset by high milk yield alone. The key to this difference lies in the different management practices under which animal manures were treated, and their different associated levels of emissions. Under the Low forage regime, 100% of the fully housed lactating cows' excreta was stored under anaerobic conditions as liquid slurry. The default emissions factor for direct nitrous emissions from animal manures (EF<sub>3</sub>), when maintained in liquid storage without a crust as practised at CRF, is zero (IPCC, 2006). In contrast, lactating High forage cows spent an average of 148 (sd=15) full days annually at pasture, where the emissions factor for deposition of animal manures (EF<sub>3PRP</sub>) is recommended as 0.02 kg N<sub>2</sub>O-N per kg nitrogen deposited (IPCC, 2006). This factor is also 4 times higher than 0.005 kg N<sub>2</sub>O-N per kg stipulated for solid storage of farm manure. Thus under the Low forage regime and Select line, emissions from the increased excreted lost nitrogen associated with higher productivity did not result in a higher contribution to GWP from animal manures.

#### *3.4.1.3 Balance of emissions within LCA boundary*

The results of this LCA study permitted examination of not only the effect of production system on the balance between enteric CH<sub>4</sub> and emissions from manure nitrogen. Striving towards efficiency in one aspect can inherently impact upon other contributing sources of GHG emissions, for example methane from manure, and emissions associated with manufactured fertilisers and the production of purchased feeds. The methane conversion factor (MCF) given by the IPCC for animal manures under liquid storage is 17% (IPCC, 2006). As a result of the 100% liquid storage of excreta, resulting gross manure CH<sub>4</sub> emissions were greater under the Low forage regime than they would have been if stored as solid manure (MCF=2%) or deposited at pasture (MCF=1%). In spite of this, LF groups were still observed to be more

efficient in terms of manure CH<sub>4</sub> per unit ECM, with a GWP around 31% lower in Low forage regime.

The contribution of N<sub>2</sub>O from applied manufactured fertilisers to the overall GWP, estimated to be around 3-5% in LF and 4-7% in HF, was lower than the UK average of 8% stated in a recent study (DairyCo, 2012a). This can be explained by CRF management adopting a more efficient use of organic manure slurry through employing slurry injection. The LCA model used the standard IPCC emissions factors for direct and indirect emissions from applied organic manure nitrogen, thus could not account for any difference in the level of ammonia or N<sub>2</sub>O emissions from injected slurry. However, the management practice enabled a substantial reduction in the quantity of manufactured fertilisers required, along with their emissions both on-farm and the environmental cost of their production. However, inorganic nitrogen fertiliser was still routinely applied to crops and pasture at CRF, at an average application rate of 87 kg nitrogen ha<sup>-1</sup> (sd=22) over the period. On-farm land use was estimated to be 0.59, 0.53, 0.98 and 0.88m<sup>2</sup> kg<sup>-1</sup>ECM for LFC, LFS, HFC and HFS respectively. High forage regime was estimated to require on average around 0.37m<sup>2</sup> more on-farm land per kgECM than Low forage regime. As forage crop requirement, and thus forage crop land, was comparable across systems, this difference was therefore almost exclusively due to grazing land needed for lactating cows in HF. Select line was also estimated to require around 0.08 m<sup>2</sup> kg<sup>-1</sup> ECM more than Control, due to a higher feed intake. On-farm land use by the dairy production system was therefore a key factor in the greater manufactured fertiliser N<sub>2</sub>O emissions estimated for High forage regimes. Gross nitrous oxide emissions per livestock unit from manufactured fertiliser application were estimated to be around 40% lower in LFS compared to HFC when referenced per unit milk.

The off-farm component of manufactured fertiliser emissions, accounting for their production and delivery, was estimated to account for one-third more of the total overall GWP than the N<sub>2</sub>O emissions arising from their application. Furthermore, when combined, the total GWP associated with manufactured fertilisers amounted to 0.07-0.09 kg CO<sub>2</sub>e kgECM<sup>-1</sup> in LF and 0.11-0.13 kg CO<sub>2</sub>e kgECM<sup>-1</sup> in HF. This was greater than the contribution of N<sub>2</sub>O emissions from animal manures, and would

make the third highest contribution to overall GWP behind enteric methane and off-farm emissions associated with production of purchased feeds. This emphasises the importance of accounting for the wider off-farm emissions as well as those derived on-farm, and therefore underlines the advantages of the broader LCA approach over a simpler farm-centered analysis to ascertain a true reflection of environmental impacts of dairy production systems.

With a greater reliance on purchased feed and bedding imported onto the farm in the Low forage regime, off-farm emissions embedded in purchased goods were another important difference amongst the systems. While the life cycles of LFC and LFS systems were estimated to benefit from a lower on-farm use of manufactured fertilisers, and from their manures being retained in liquid storage, a trade-off was evident with imported feeds and bedding. Emissions associated with imported feeds and bedding was around 11% greater in LFS per unit milk compared to HFC. Indeed, embedded emissions in feeds and bedding was the only contributing source in the study in which HFC and HFS were estimated to be more efficient, with respect to GWP per unit milk, than LFC and LFS. All four systems, however, were able to benefit from the fact that a proportion of the concentrated element of their diet was sourced from by-product grains from the distilling industries. The emissions factor for by-product grain was 0.030 kg CO<sub>2</sub>e per kg of grain, compared with 0.375 and 0.360 kg CO<sub>2</sub>e per kg of directly sourced wheat and barley respectively (Carbon Trust, 2010a). This contributed to the associated GWP being lower than if all purchased feeds had been directly produced for animal consumption, as the bulk of embedded CO<sub>2</sub>e associated with the production of the grain was already taken account of in the life cycle of the distilling industry. The off-farm emissions from purchased feeds and bedding nonetheless supplied the second highest contribution to the overall GWP of the dairy production systems behind enteric CH<sub>4</sub>. The sourcing of by-product grains is therefore a key factor for all conventional dairy production systems as they attempt to minimise the GWP of their product life cycle. However, it is important to consider that if an increasing number of dairy systems switch to sourcing by-product feeds, demand may eventually exceed supply. This point is especially important for systems employing a Low forage regime, and are thus more sensitive to changes in the by-product market. It is also important to note that

purchased feed components common to all four Langhill systems were obtained from the same source. As such, this study could reasonably use the same literature values for purchased feed emissions factors across all systems. Henriksson et al. (2011) noted that purchased animal feeds, for example barley, may differ in how and where it was cultivated, transported and processed in the feed industry. Thus when making comparisons between different studies, the GWP associated with the same purchased feed components may differ. This point serves to further justify the strength of direct comparisons amongst of results in the present study.

### 3.4.2 Sensitivity Analysis

#### *3.4.2.1 Confidence in estimated global warming potentials*

Estimates of the overall GWP of dairy production systems from the LCA were found to be significantly different to each other after incorporating an account of variation both in the emissions factors and the farm derived data. This point should reinforce confidence in the robustness of the LCA results in the present study. In a similar analysis by Flysjö et al. (2011), coefficients of variation of the overall GWP were estimated to be 25.8% for an extensive New Zealand (NZ) dairy system and 16.2% for a Swedish (SW) conventional dairy production system. These values are considerably greater than those obtained in the present study, being 5.3, 5.3, 5.9 and 5.9% for LFC, LFS, HFC and HFS respectively. There are several methodological differences between the studies which may explain this, in particular the typical practices of dairy production in the respective countries. The SW/NZ study also modelled average farms through employing national level farm data as opposed to herd specific data in this analysis, and no account was made for any dependency amongst input variables. The national level study data inputs of Flysjö et al. (2011) held large standard deviations owing to the variability of management practices at farm level across entire countries. In addition, variation from farm-derived parameters, such as DMI and milk yield, were omitted in the SW/NZ Monte Carlo simulations in order to eliminate the confounded variation in the estimated GWP of milk due to farm management practices (Flysjö et al., 2011). However, in the present study, the aim of the simulation was to account for the total potential variation introduced by both farm data and emissions factors. Furthermore, confounding



effects of farm management were limited by the use of populations of dependent variables for the on-farm data. It is noted, however, that in both analyses the coefficient of variation was greater for the systems which had a greater dependency on grazing pasture. In this study, annual time spent grazing under High forage regime ranged from 125 to 165 full days at grass over the period, introducing an element of variation not present in Low forage regime. For High forage regime, the N<sub>2</sub>O emissions from deposition at pasture, storage of animal manures, forage crop requirements and purchased feed intake (along with associated embedded emissions) were all dependent on the variation introduced by the time spent at grass, which was not the case for systems on the more intensive Low forage regime.

#### *3.4.2.2 Key variables contributing to uncertainty*

The second objective of the sensitivity analysis was to identify which parameters contributed the most to uncertainty in estimated GWP. Sources contributing the most uncertainty to results were N<sub>2</sub>O emissions from management of manures, and enteric fermentation. This is broadly concurrent with Basset-Mens et al. (2009b) and Flysjö et al. (2011) who found that, in similar analyses, the key parameter contributing the highest uncertainty was the emissions factor for direct N<sub>2</sub>O emissions from excreta deposited directly on grazing (EF<sub>3PRP</sub>), followed by CH<sub>4</sub> emissions from enteric fermentation. Both Basset-Mens et al. (2009b) and Flysjö et al. (2011) employed a NZ specific emissions factor for deposition at pasture, 50% lower than the IPCC default value, however this factor still produced the highest uncertainty in their respective studies. Within the N<sub>2</sub>O emissions from animal manures in the present study, however, the coefficient governing indirect emissions from volatilised nitrogen (EF<sub>4</sub>) was found to be the dominant factor. Under High forage regime, EF<sub>3PRP</sub> was found to contribute the next greatest amount of variation to emissions from manures after EF<sub>4</sub> and the system specific nitrogen excretion rate, while the parameter was not applicable to Low forage regime. Difference between the studies can be explained by the observation that Basset-Mens et al. (2009b) based their analysis on an extensive grazing-based New Zealand dairy production system. It is likely therefore, that the effect of variation introduced by EF<sub>3PRP</sub> is the reason for the greater coefficient of variation observed in the High forage groups. Flysjö et al. (2011) stated that the parameter for grazing deposition emissions caused the highest

change in GWP for the NZ system, but also state that a greater GWP associated with fossil fuels in SW was likely responsible for the observed difference between systems in the SW/NZ study.

#### *3.4.2.3 Minimising level of uncertainty*

Although enteric fermentation contributed the most (46-49%) to the total GWP in all systems, this source did not contribute the most uncertainty overall. Expressed a different way, enteric CH<sub>4</sub> had a GWP four times greater than N<sub>2</sub>O from animal manures under the High forage regime, and six times greater under Low forage regime, yet animal manure emissions made a larger contribution to the overall uncertainty. This goes to highlight that, for as much as a LCA methods may seek to minimise the variation in its farm inventory data, a greater and unavoidable component of the uncertainty in LCA results will arise from employing standardised emissions factors. The IPCC coefficient for indirect emissions from volatilised nitrogen (EF<sub>4</sub>) was found to be the dominant factor contributing to overall uncertainty, while the coefficient for deposition at pasture (EF<sub>3PRP</sub>) was a key contributor for High forage systems, as was the coefficient for direct N<sub>2</sub>O emissions (EF<sub>1</sub>) for all systems. The uncertainty range for EF<sub>4</sub> stated in the literature amounts to a factor of 25, while uncertainties in EF<sub>1</sub> and EF<sub>3PRP</sub> range by a factor of 10 and by around 8.5 respectively (IPCC, 2006). These standardised emissions factors necessarily contain a large uncertainty range as they aspire to be representative of the range of natural variability and physical conditions found on a national scale. In the present study, Tier 3 enteric CH<sub>4</sub> emissions factors by contrast were noted to have a coefficient of variation of around 7-10% across all systems. This point illustrates a further advantage of employing system-specific emissions factors in the present study or, more generally, employing Tier 3 values where possible in the LCA of dairy production systems. The IPCC note that variation introduced by any Tier 3 emissions factors employed is likely to be minimised, while uncertainties introduced by standardised emission factors are likely to dominate (IPCC, 2006). Thus after many studies have gone to lengths to define and standardise the LCA methods, perhaps the most crucial aspect for confidence in LCA results in the future lies with narrowing the uncertainty parameters surrounding IPCC emissions factors, and developing countries' respective Tier 2 and Tier 3 coefficients. The present study

suggests that increased definition of the inventory coefficients  $EF_1$  and  $EF_4$  would increase confidence in the estimated GWP of all dairy production systems, while minimising uncertainty in  $EF_3$  would improve confidence in LCA results for those systems which involve grazing pasture.

### 3.5 Conclusions

The aim of this study was to assess the global warming potential of four different systems by employing Life Cycle Analysis. Dairy production systems under examination were all contained within the same farm, therefore results were directly comparable with one and other. The LFS system, where high genetic merit cows were managed under a Low forage regime, was the most environmentally efficient system with respect to global warming potential per unit of milk production. Methane from enteric fermentation contributed the highest to global warming potential of all four systems. However, key factors in the differences amongst systems were greater off-farm gross emissions under Low forage regime, and greater on-farm nitrous oxide emissions associated with High forage. In Low forage groups, high gross emissions were matched with increased productivity, but this was not the case for the more extensive High forage groups.

This study also aimed to examine the effect of uncertainty in data and emissions factors on the GWP of the dairy production systems. Six key variables were identified to contain the greatest influence on uncertainty in results. These included three IPCC coefficients concerning nitrous oxide emissions, and three Tier 3 emissions factors concerning cows' enteric fermentation, manure methane and excreted nitrogen rate. The IPCC coefficients for indirect emissions from volatilised nitrogen ( $EF_4$ ), direct atmospheric  $N_2O$  emissions ( $EF_1$ ), and emissions from deposition at pasture ( $EF_{3\text{ PRP}}$ ) should be prioritised for better definition in order to minimise uncertainty in future studies.

## **Chapter Four**

## **Chapter 4**

### **Merit of different Functional Units describing the Global Warming Potential of Dairy Production Systems**

#### **4.1 Introduction**

##### **4.1.1 Background**

Life Cycle Assessment (LCA) has become a leading tool employed in agriculture for environmental impact and greenhouse gas (GHG) emissions accounting at whole systems level. Favoured for its flexibility, LCA enables an account to be made of all system inputs, processes and outputs within a specified boundary. In order to improve transparency and consistency amongst studies, the International Organization for Standardization (ISO) established the international standard ISO 14040 (ISO, 2006), stipulating requirements and recommendations for the LCA decision making process. Further frameworks attempting to institute consistency in LCA at national and industry specific levels have been developed, such as PAS 2050 in the United Kingdom (BSI, 2011). Audsley et al. (1997) investigated the application of LCA to agriculture, identifying methodological difficulties of the process and harmonising various approaches which were employed by the industry

Life Cycle Assessment has been implemented to determine the global warming potential (GWP) of dairy production systems at national levels of various countries (Cederberg and Flysjo, 2004; Basset-Mens et al., 2005; Casey and Holden, 2005a; McGeough et al., 2012) and in comparisons between organic and conventional production systems (Cederberg and Mattsson, 2000; de Boer, 2003; Thomassen et al., 2008b). Previous LCA studies have also looked at the effect of implementing different GHG accounting methods (O'Brien et al., 2011), and different approaches to the allocation of GWP to co-products (Cederberg and Stadig, 2003; Thomassen et al., 2008a; Rotz et al., 2010; Kristensen et al., 2011). Other studies have also examined the effect of uncertainty in farm data (Gibbons et al., 2006) or uncertainty in emissions factor coefficients (Basset-Mens, 2009b; Flysjö et al., 2011), while Crosson et al. (2011) and Yan et al. (2011) conducted reviews of the application of LCA in dairy.

By convention the results of LCA must be referenced to a functional unit (FU), providing a clearly defined and measurable reference to which input and output data are normalised (ISO 2006). The British Standards Institute (BSI) state that, for the purposes of GHG measurement, the FU can be a single item of product or a generally accepted sales quantity (BSI 2011). The selection of an appropriate FU is crucial when assessing environmental impacts and interpreting the results, because an impact category such as GWP may be referenced to several different FU (Haas et al., 2001). In LCA of dairy production systems, the FU has most commonly been in the form of a unit of milk, the principle unit of production in dairy. Although concerted efforts have been made to establish consistency in the application of LCA to dairy production systems, the definition of specific FU ultimately remains at the discretion of the individual investigators. A review of 25 dairy LCA studies in the literature revealed the range of FU which have been employed. A summary of the different FUs that have been used in different studies is presented in Table 4.1.

**Table 4.1: Functional units (FU) employed in 25 Life Cycle Analysis (LCA) studies of dairy production systems in literature**

Study	Year	Functional Unit							
		LU	Milk	ECM	FPCM	MS	ha <sub>farm</sub>	ha <sub>total</sub>	Other
Cederberg and Mattsson	2000			✓					
Haas et al.	2001	✓	✓				✓		
Berlin	2002								kg cheese
Cederberg and Stadig	2003			✓					
Hospido et al.	2003								packaged milk
Cederberg and Flysjo	2004			✓					
Basset Mens et al.	2005			✓					
Casey and Holden	2005a			✓					
Casey and Holden	2005b			✓				✓	
Saunders and Barber	2007					✓		✓	
Thomassen et al.	2008a				✓				
Thomassen et al.	2008b				✓				
Basset Mens et al.	2009a		✓					✓	
Thomassen et al.	2009				✓				
van der Werf et al.	2009				✓		✓	✓	
Muller-Lindenlauf et al.	2010		✓						
Rotz et al.	2010			✓					
Bell et al.	2011			✓					
Hagemann et al.	2011			✓					
Kristensen et al.	2011			✓					
McGeough et al.	2011				✓				
O'Brien et al.	2011		✓			✓		✓	
DairyCo	2012a								FCM
Fantin et al.	2012								litre milk
O'Brien et al.	2012				✓	✓	✓	✓	

Where: LU = livestock units, Milk = kg of raw milk, ECM = kg of energy corrected milk, FPCM = kg of fat and protein corrected milk, MS = kg of milk solids (fat+protein), ha<sub>farm</sub> = hectares of land-use on farm, ha<sub>total</sub> = hectares of combined land-use on farm plus land-use in external production of purchased feeds, FCM = litres of fat corrected milk. Packaged milk includes cost of processing and packaging milk ready for consumer.

As a FU, milk yield has commonly been corrected to standardised levels of butterfat and protein content, as milk composition commonly determines the value of raw milk to the processor. This enables a better comparison between farms with different breeds or different feeding regimes (IDF, 2010). Energy corrected milk (ECM), as defined by Sjaunja et al. (1990), has been the most widely applied FU. Many LCA of dairy systems studies have implemented an alternative FU of fat and protein corrected milk (FPCM), and this is also the unit recommended by the International Dairy Federation (IDF, 2010). These two different FU are defined by the different levels of fat and protein content to which they standardise milk yields. A selection of other production based FU have been employed, including the combined mass of milk fat and protein as milk solids (MS), or simply as uncorrected raw milk yields. Furthermore, where the LCA boundary included post-farm processing of dairy products, results have sometimes been referenced to a unit of consumer produce, such as a litre of processed packaged milk (Hospido et al., 2003) or a kilogram of specific product cheese (Berlin, 2002).

Expressing the GWP per unit of productivity is essentially a ratio of undesirable versus desirable outputs, and does not therefore conform to a more conventional definition of efficiency as output versus input. Land-use, however, is another FU that has commonly been utilised to reference the results from LCA of dairy production systems, and does satisfy this definition as a measure of a systems output versus a systems input. Similar to productivity, land-use has been presented in several different forms, for example the productive on-farm land required for grazing and forage production, or the entire farm area including buildings. More frequently in LCA of dairy production systems however, land use has incorporated the total on- and off-farm land contributing to productivity, where off-farm included land required to produce purchased and concentrated feeds. Rotz et al. (2010) compared dairy systems' emissions intensity per cow, but this was not the stated FU for the study. A review of the literature found only one LCA study which employed the livestock themselves as a FU, expressed as the total number of livestock units on the farm (Haas et al., 2001). Employing livestock units enables the entire herd to be included, for example sold calves that consumed feed and created emissions/manure, by correcting for the relative ages and persistence of young and replacement animals.

In the literature there has not so far been a study conducted specifically to examine the effect of varying the FU on the results of LCA of different dairy production systems. Several studies have employed multiple FUs, therefore indirectly providing some assessment, albeit not necessarily as the primary aim of the studies. For example, O'Brien et al. (2012) compared a seasonal grazing dairy production system with a confinement system in Ireland, employing four different FU. The grazing system was found to have lower GWP per FU in three instances (FPCM, MS, on-farm land), while the confinement system was found to have lower GWP per hectare of total land used (O'Brien et al., 2012). In a German study comparing organic and conventional dairy production systems, the organic system was found to have a lower GWP both per hectare on-farm land and total area. However, the study found there was no difference between the systems in terms of their GWP per kg FPCM (van der Werf et al., 2009). Haas et al. (2001) found that both the GWP per hectare and per livestock unit were lower for organic dairy production systems compared to conventional extensive and intensive systems. Per unit milk, however, GWP was lowest for the extensive system, and there was no difference between the intensive and organic systems (Haas et al., 2001). The results of these three studies in the literature demonstrate that the perceived relative environmental efficiency of dairy production systems could change based on which FU was employed to present the results.

Functional units employed in the literature have tended to be based upon a single variable, such as a hectare of land, a kilogram or litre of milk. Hayashi (2013) stated that an area and product based unit could be combined to provide integrated criteria for assessment, using the units complementarily. This approach could thus reflect improvements made in the biological efficiency of animal production and efficiency of either crop production or land-use. There is however, no literature evidence of studies incorporating two variables into a single FU, for example both productivity (output) and land use (input).

#### 4.1.2 Aims and objectives

The aim of this chapter was to examine the effect of employing different functional units on the relative environmental efficiency of four dairy production systems.



Global warming potential of dairy production systems was to be determined by life cycle analysis, and referenced to five functional units previously employed by LCA studies in the literature. The study aimed to assess the merit and suitability of each functional unit, examining the reasons underlying their effect on the balance of GWP amongst directly comparable systems. This chapter also aimed to compare and assess the worth of an original ‘dual’ functional unit which incorporated both the productivity and land requirements of a dairy production system.

## 4.2 Materials and Methods

### 4.2.1 Dairy production systems and life cycle analysis

The study was based on four dairy production systems using the Langhill herd based at SRUC Dairy Research Centre, Dumfries. Two forage regimes (High Forage (HF) and Low Forage (LF)) were applied to each of two genetic lines (Select (S) and Control (C)) giving four contrasting production systems (HFS, HFC, LFS and LFC) within the same farm. Employing LCA, the GWP of each system was estimated for each of seven calendar years (2004-2010) in terms of kg CO<sub>2</sub>-equivalents (kg CO<sub>2</sub>e) per FU. Detail of the Langhill dairy production systems and LCA methods have previously been reported in chapter 3 of this thesis. The most GHG efficient system was defined as the lowest emissions per FU.

### 4.2.2 Functional units

Five FU, which had been employed in previous LCA studies of dairy production systems, were selected for this analysis. The effect of an original FU, which incorporated a measure of both the productivity and land use of the systems, was also examined. The estimated annual GWP of dairy production systems was thus referenced to six different FU as described in table 4.2.

**Table 4.2: Description of functional units employed analysis**

Functional Unit	Abbreviation	Units
Livestock unit	LU	kg CO <sub>2</sub> e LU <sup>-1</sup>
Energy corrected milk yield	ECM	kg CO <sub>2</sub> e kg <sup>-1</sup> ECM
Total combined milk solids yield	MS	kg CO <sub>2</sub> e kg <sup>-1</sup> MS
On-farm land used for production	Land <sub>farm</sub>	kg CO <sub>2</sub> e ha <sup>-1</sup>
Combined on- and off-farm land used for production	Land <sub>total</sub>	kg CO <sub>2</sub> e ha <sup>-1</sup>
Energy corrected milk per unit of total land used	ECM/Land <sub>total</sub>	kg CO <sub>2</sub> e t <sup>-1</sup> ECM ha <sup>-1</sup>

A breakdown of detail underpinning each FU is provided in the ensuing sub-sections.

#### 4.2.2.1 Livestock

The simplest FU to be assessed in this analysis accounted for the number of livestock in each production system. At system level the LCA accounts for GHG pollutants produced by not only the milking cows but also the replacement and young stock, which pollute at different levels depending on their age and diet. Livestock units (LU) were therefore used to weight populations of different age categories of livestock within each system. These were defined for heifers aged 0-12 months, heifers 12-24 months and heifers over 24 months, as being 0.34, 0.65 and 0.80 respectively (DEFRA, 2010). Factors for cows were corrected for average liveweight and milk yield (ADAS, 1983), and defined as 1.48, 1.64, 1.26 and 1.37 for LFC, LFS, HFC and HFS respectively. Total populations of each livestock category were multiplied by their respective coefficients and summed to give a corrected average population in LU for each system each year. A breakdown of the average herd populations expressed in LU for each system each year is displayed in Table 4.3.

**Table 4.3: Average population present in each livestock category of the Langhill dairy production systems each year of the study, presented as livestock units (LU)**

System	Livestock category	Year of study						
		2004	2005	2006	2007	2008	2009	2010
LFC	cows	62.8	69.5	71.7	73.9	73.2	73.2	74.7
	heifer >24	4.8	3.2	2.8	2.4	1.2	1.2	1.6
	heifer 12-24	9.8	10.4	13.7	14.6	13.7	16.6	19.2
	calf 0-12	5.6	7.1	7.3	6.8	8.7	10.0	8.8
	Total LU	83.0	90.2	95.5	97.8	96.7	101.0	104.3
LFS	cows	59.8	59.0	65.6	71.3	71.3	77.9	86.1
	heifer >24	2.8	5.2	6.0	2.8	1.2	0.8	0.4
	heifer 12-24	10.1	12.7	9.8	9.4	12.0	11.7	14.6
	calf 0-12	7.0	5.3	4.9	6.3	6.3	7.8	8.0
	Total LU	79.7	82.2	86.2	89.8	90.8	98.2	109.1
HFC	cows	53.7	61.9	65.7	66.3	67.5	69.4	69.4
	heifer >24	5.2	6.4	4.8	5.2	4.0	2.4	3.6
	heifer 12-24	10.7	10.7	15.6	15.3	13.3	17.9	18.9
	calf 0-12	5.8	8.2	8.2	7.3	9.7	10.0	10.0
	Total LU	75.4	87.1	94.2	94.1	94.6	99.7	101.9
HFS	cows	57.4	63.6	64.3	64.3	69.1	74.5	74.5
	heifer >24	4.8	4.0	3.6	3.2	2.0	2.4	3.2
	heifer 12-24	7.5	9.1	11.1	11.7	12.0	14.0	15.3
	calf 0-12	4.8	6.0	6.3	6.3	7.5	8.2	7.3
	Total LU	74.5	82.6	85.2	85.5	90.6	99.1	100.3

Where: LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select, and; LU= livestock units, cows = lactating or dry cows (=1.48, 1.64, 1.26 and 1.37LU for LFC, LFS, HFC and HFS respectively), heifer>24 = pregnant heifers older than 24 months (=0.8LU), heifer 12-24 = heifers aged between 12-24 months (=0.65LU), and calf 0-12 = heifer calves 0-12 months(=0.34LU).

#### 4.2.2.2 Energy corrected milk

Milk yields amongst different production systems varied in the amount of energy they contain, potentially leading to differences in calculations if only the mass or volume of milk was considered. The average milk yield per cow, milk fat and protein content of the four systems over the study period are presented in Table 4.4.

**Table 4.4: Average productivity of Langhill dairy production systems 2004-2010**

Characteristic	Units	Production System							
		LFC		LFS		HFC		HFS	
		mean	sd	mean	sd	mean	sd	mean	sd
Milk fat	g kg <sup>-1</sup>	35.4	0.18	37.8	0.18	38.2	0.18	40.0	0.19
Milk protein	g kg <sup>-1</sup>	31.5	0.09	33.7	0.09	32.1	0.09	33.5	0.01
Milk yield	kg cow <sup>-1</sup> yr <sup>-1</sup>	9246	800	10753	853	7281	533	8189	656

Where: LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, and LFS = High Forage Select

In the dairy industry various equations are available to correct a mass of milk while considering both its fat and the protein content. The equation of Sjaunja et al. (1990) standardises milk yields to contain 35.0g kg<sup>-1</sup> butterfat and 32.0g kg<sup>-1</sup> protein. Presented below as Equation 4.1, this equation was selected as appropriate for the present study and has been most widely applied in previous LCA studies. The total annual raw milk yield of each system each year of the study was corrected using systems' respective estimated mean annual milk fat and protein content.

#### **Equation 4.1: Energy corrected milk (ECM) by Sjaunja et al. (1990)**

$$\text{ECM (kg)} = 0.25M + 12.2F + 7.7P$$

where M = annual milk yield (kg), F = fat content (kg), P = protein content (kg)

#### 4.2.2.3 Milk solids

Data on milk yields were recorded for individual cows after every milking session. Milk fat and protein content were recorded from samples collected from each cow, three times daily on one day each week. An estimate was thus made for the total mass of milk fat and protein yielded by each cow in each calendar year. Individual cow data were combined to give the total annual output of milk solids (MS) for each system.

#### *4.2.2.4 On-farm land-use*

On-farm land-use for provision of forage crops to each system was estimated based on the forage requirements of the system. Yields of forage crops (ryegrass silage, wholecrop wheat, maize) per hectare and their dry matter content were noted at ensilage following harvest. Quantities of ensiled forages used were weighed during formulation of the daily TMRs and daily feed intake of cows recorded using automated Hoko feeding gates (Insentec BV, Marknesse, The Netherlands). Forage crop requirements of each system were then related to the harvested forages and the annual forage land requirement was estimated for each system. Dry matter losses were considered during harvesting (categorised as mechanical, respiration, wilting and leaching losses), ensiling (surface, effluent and invisible losses) and unloading (mechanical losses) of forages (Bastiman and Altman, 1985; MacDonald et al., 1991). Land required by HF systems for pasture was similarly estimated based upon the predicted grazing DMI of cows and the available herbage per hectare. Bell et al. (2010) estimated DMI at grazing, based on the cows energy balance, to be 19.2 and 20.8 kg cow<sup>-1</sup> day<sup>-1</sup> (s.e. = 0.5) for Control and Select herds at Crichton Royal Farm respectively over the period from 2004 to 2008.

#### *4.2.2.5 Off-farm land-use*

Off-farm land associated with the external production of purchased feed components and bedding was estimated employing a similar method to that of Bell et al. (2011b). Total annual purchased feed required was estimated from recorded Hoko data and TMR formulations for milking cows, and from ration formulations for dry and replacement stock. The purchased fraction of the diets was then broken down into their component ingredients. Land-use values for domestically produced purchased feed components (wheat, rapeseed, barley) were estimated employing Scottish-specific data on crop yields (Craig & Logan, 2012; Scottish Government, 2012), and English data for sugarbeet yields (DEFRA, 2011b). A land-use value for the internationally imported feed component (soyabean meal) was sourced from the LCA food database (Neilsen et al., 2003). Data sourced were for whole crop yields, which were converted to land use values before allocating amongst co-products. Allocations between co-products of purchased feed components, for example

rapeseed meal and oil, were made using the allocations identified by Cederberg and Mattson (2000). Data did not account for fermentation residues. Estimated land-use values for one kilogram of purchased feed blends for high forage (HF), low forage (LF) and young stock (YS) diets are presented in Table 4.5.

**Table 4.5: Estimated off farm land use associated with one kilogram of purchased concentrated feed blend for High Forage (HF), Low Forage (LF) and Young Stock (YS)**

Component	Whole Crop Yield <sup>a</sup> tDM ha <sup>-1</sup>	Allocation <sup>b</sup> %	Land use m <sup>2</sup> kg <sup>-1</sup>	Land use per kg feed blend		
				HF m <sup>2</sup> kg <sup>-1</sup>	LF m <sup>2</sup> kg <sup>-1</sup>	YS m <sup>2</sup> kg <sup>-1</sup>
Wheat	7.0	100	1.43	0.429	0.637	0.206
Sugar beet pulp	10.0	22	0.22		0.059	0.049
Sugar beet molasses	10.0	12	0.12			0.003
Soyabean meal	3.0 <sup>c</sup>	80	2.64		0.753	0.147
Rapeseed meal	3.9	60	1.55	0.695		0.086
Barley	5.9	100	1.71	0.425		0.855
Complete blend				1.551	1.439	1.345

<sup>a</sup>Average whole crop yields derived from: Craig & Logan (2012)/Scottish Government (2012)/DEFRA (2011b),

<sup>b</sup>Allocations from Cederberg and Mattson (2000). <sup>c</sup>Value for soya land use from Neilsen et al (2003).

The on-farm, off-farm and total combined land requirements were estimated for each production system in each year of the period. Mean annual land requirements are presented in Table 4.6, expressed per LU to permit comparison between systems.

**Table 4.6: Land requirement per livestock unit of Langhill dairy production systems**

Characteristic	Units	Production System							
		LFC		LFS		HFC		HFS	
		mean	sd	mean	sd	mean	sd	mean	sd
On-farm land	ha LU <sup>-1</sup>	0.34	0.05	0.40	0.06	0.47	0.07	0.52	0.07
Off-farm land	ha LU <sup>-1</sup>	0.54	0.06	0.62	0.08	0.20	0.02	0.20	0.02
Total land	ha LU <sup>-1</sup>	0.89	0.10	1.02	0.13	0.66	0.09	0.72	0.09

Annual required land areas averaged over the study period and expressed in hectares (ha) per livestock unit (LU) to permit comparison between systems. Estimated on-farm land incorporates all productive land required to provide forage crops, bedding and grazing pasture where appropriate. Off-farm land includes land required for production of purchased animal feeds. Total land represents the combined on- and off-farm land.

#### 4.2.2.6 Proposed dual functional unit

The original FU proposed for this study included both the productivity and land-use of the systems. The estimated annual GWP of the dairy production system was divided by the total annual ECM yield, and this quotient further divided by the total annual land-use of the system for each year of the study. This ‘dual’ FU thus incorporated the ratio of undesirable output (GHG) to desirable output (milk) per unit input (area of land), therefore adhered to a more standardised output/input measure of efficiency.

#### 4.2.3 Statistical analysis

Two different statistical procedures were employed in this analysis. The effect of employing different FU upon the estimated environmental efficiency of dairy production systems was assessed by analysis of variance (ANOVA), using numerical data. The effect of different FU upon the relative efficiencies amongst systems was assessed by rank analysis, using non-parametric rank data. All statistical analysis was conducted using Minitab 16.

##### 4.2.3.1 Generalised linear model

Analysis of variance was conducted employing a generalised linear model (GLM).

The model used was:  $y_{ij} = \mu + S_i + Y_i + \epsilon_i$

where  $y_i$  was the total global warming potential of the dairy production system per functional unit (LU, ECM, MS,  $\text{Land}_{\text{farm}}$ ,  $\text{Land}_{\text{total}}$ ,  $\text{ECM}/\text{Land}_{\text{total}}$ );  $\mu$  was the overall mean;  $S_i$  was the fixed effect of dairy production system (LFC, LFS, HFC, HFS);  $Y_i$  was the random effect of calendar year (2004-2010);  $\epsilon_{ij}$  was the random error term. Fisher tests were used to assess the level of significance of contributing effects, and differences between dairy production systems were determined conducting pairwise comparisons using the Tukey method.

##### 4.2.3.2 Rank analysis

Rank analysis was performed in order to assess the effect of employing different FU on the relative order of the systems' estimated environmental efficiencies. Using year as a repeated measure, systems were assigned a rank value from 1 to 4 in order of their relative environmental efficiency each year. Rank 1 was noted as having the lowest GWP per FU and thus most efficient system, and 4 the highest GWP per FU, thus least efficient. Rank analysis was performed using the Kruskal-Wallis test, which served as a non-parametric equivalent to ANOVA. Significant differences between any two systems were assessed using the Mann-Whitney-Wilcoxon rank sum test. The rank analysis was repeated when referencing the GWP of systems to each of the six FU employed in this study.

## 4.3 Results

### 4.3.1 Environmental efficiency

The effect of the dairy production system on the overall GWP per FU was found to be highly significant ( $P < 0.001$ ) when each of the six different FU were applied. Least squares mean values determined for the GWP of each system per FU are presented in Table 4.7.

**Table 4.7: Global Warming Potential (GWP) of Langhill dairy production systems expressed as kilograms of carbon dioxide equivalents (kgCO<sub>2</sub>e) per functional unit (FU)**

Variable	Level	Functional Unit					
		LU LU <sup>-1</sup>	MY kg <sup>-1</sup> ECM	MS kg <sup>-1</sup> MS	Land <sub>farm</sub> ha <sup>-1</sup>	Land <sub>total</sub> ha <sup>-1</sup>	MY/Land <sub>total</sub> t <sup>-1</sup> ECM ha <sup>-1</sup>
System	LFC	4126 <sup>a</sup>	0.92 <sup>a</sup>	12.9 <sup>a</sup>	16006 <sup>a</sup>	6278 <sup>a</sup>	14.9 <sup>a</sup>
	LFS	4398 <sup>ab</sup>	0.83 <sup>b</sup>	11.4 <sup>b</sup>	15971 <sup>a</sup>	6304 <sup>a</sup>	13.4 <sup>a</sup>
	HFC	4535 <sup>bc</sup>	1.10 <sup>c</sup>	15.2 <sup>c</sup>	11506 <sup>b</sup>	8041 <sup>b</sup>	21.4 <sup>b</sup>
	HFS	4807 <sup>c</sup>	1.00 <sup>d</sup>	13.7 <sup>a</sup>	11704 <sup>b</sup>	7467 <sup>b</sup>	20.5 <sup>b</sup>
	sem	126.3	0.016	0.23	252.5	236.2	0.82

Different superscripts within a column denote significant differences between levels of same variables, ( $P < 0.001$ ) Results presented as least squares means (ls) with standard error of the mean (sem). FU include: livestock units (LU), total energy corrected milk yield (MY), total milk solids (MS), on-farm land use (Land<sub>farm</sub>), total land use (Land<sub>total</sub>), and milk yield per unit total land used (MY/Land<sub>total</sub>).

Energy corrected milk yield was the only FU which resulted in the GWP of all four systems being significantly different from each other. LFS was observed to have the lowest GHG emissions per kg ECM, followed by LFC, HFS and HFC respectively. Using milk solids as the FU, LFS was again found to be the most GHG efficient system and HFC the least efficient. There was no significant difference between LFC and HFS per kilogram of milk solids. When livestock units was the FU employed, LFC was found to be the most efficient, although not significantly different to LFS. Livestock unit was the only FU employed in this study which did not find a significant difference between LFS and HFC. Employing Land<sub>farm</sub> as the FU, the GWP per hectare of both the High Forage systems was found to be lower than the Low Forage systems. Conversely, when including off-farm land use, the two Low Forage systems were found to be more efficient in terms of GWP per hectare than the

two High Forage systems. Employing the dual FU incorporating both productivity and land use, the two LF systems were also found to be more efficient than the two High Forage systems. However, none of the three FU which incorporated land-use found a significant difference between either HFC and HFS, or between LFC and LFS. Overall, LFS was found to be the most efficient system when employing four out of the six FU (ECM, MS, Land<sub>total</sub>, ECM/Land<sub>total</sub>).

#### 4.3.2 Rank analysis

When employing each of the six FU, the median rank values for relative environmental efficiency of dairy production systems were found to be significant ( $P < 0.001$ ). Systems' median efficiency rankings using each FU are presented in Table 4.8, with significant differences amongst ranks determined by Mann-Whitney-Wilcoxon rank sum test.

**Table 4.8: Relative rankings for Langhill dairy production systems in terms of Global Warming Potential (GWP) per functional unit (FU), presented as median values**

Variable	Level	Functional Unit					
		LU	ECM	MS	Land <sub>farm</sub>	Land <sub>total</sub>	ECM/Land <sub>total</sub>
System	LFC	1 <sup>a</sup>	2 <sup>a</sup>	2 <sup>a</sup>	3 <sup>a</sup>	1 <sup>a</sup>	2 <sup>a</sup>
	LFS	2 <sup>b</sup>	1 <sup>b</sup>	1 <sup>b</sup>	4 <sup>a</sup>	2 <sup>a</sup>	1 <sup>b</sup>
	HFC	3 <sup>b</sup>	4 <sup>c</sup>	4 <sup>c</sup>	1 <sup>b</sup>	3 <sup>b</sup>	4 <sup>c</sup>
	HFS	4 <sup>c</sup>	3 <sup>d</sup>	3 <sup>a</sup>	2 <sup>b</sup>	4 <sup>c</sup>	3 <sup>c</sup>

Functional units include: livestock units (LU), total energy corrected milk yield (ECM), total milk solids (MS), on-farm land use (Land<sub>farm</sub>), total land use (Land<sub>total</sub>), and milk yield per unit total land used (ECM/Land<sub>total</sub>). Different superscripts within columns denote significant ( $P < 0.05$ ) differences between median values determined by Mann-Whitney-Wilcoxon rank sum test

The median rank values obtained using each FU broadly reflected the relative order of systems' efficiency observed from ANOVA results. However, there were two apparent differences between results from the ANOVA and the rank analysis. Using Land<sub>total</sub> as the FU, the HFS system was observed to be the least GHG efficient production system, and significantly different to the 3<sup>rd</sup> ranked HFC. Furthermore, the two systems estimated to be most efficient when using the dual FU, LFS and LFC, were found to be significantly different to each other by the Mann-Whitney-Wilcoxon rank sum test, with LFS having the lowest GWP. The LFS system was



thus found to be ranked the most GHG efficient system per unit ECM, per unit MS and per ECM/Land<sub>total</sub>. LFS was also the most efficient per unit Land<sub>total</sub>, although this was not significantly different to LFC. However, when employing livestock units or on-farm land as the FU, LFS was observed to be the least GHG efficient system. Therefore LFS was estimated to be the most efficient system when employing four of the FU and the least efficient when using the remaining two. Similarly, the HFC system was found to be most efficient employing two FU, but the least efficient when using three other FU.

#### 4.4 Discussion

The aim of this chapter was to assess the effect of employing different functional units on the environmental efficiency of four dairy production systems. This permitted assessment of whether the perceived environmental efficiency of a system was consistent across a range of FU available in the literature. Furthermore, a comparison of results was made with a proposed new functional unit which aimed to account for both the productivity and land use of a system. The reasons and context underlying observed differences amongst systems must be clearly understood, and hold implications for the way in which LCA results are interpreted.

##### 4.4.1 Merit of functional units

###### *4.4.1.1 Livestock units*

Livestock units are commonly used in the dairy industry, for example to compare stocking densities and nutritional requirements of animals. However, livestock have been infrequently used as a FU when interpreting outputs from LCA studies. With regards to livestock units as a FU, the two systems with the lowest GWP per FU were found to be of the Low Forage regime. Haas et al. (2001) reported that when emissions were referenced to LU (defined as 500kg of cow bodyweight), the extensive grazing-based systems appeared more favourable than intensive systems. This trend was not reflected in the results of the present study. Considering the higher overall emissions associated with the Low Forage regime (noted in chapter 3), and that Langhill systems were maintained with comparative numbers of milking

cows, the observed difference was likely due to greater animal performance under Low Forage. The UK livestock unit is based on a standard of 48,000 MJ of metabolisable energy (ME), defined as “the feed energy allowance of a 625 kg Freisian cow and the production of a 40 kg calf, and 4,500 litres of milk at 3.6% butterfat and 8.6% solids-not-fat” (ADAS, 1983, DEFRA, 2010). Adjusting the number of livestock units in each system based on corrections for liveweight and productivity stipulated by ADAS (1983), differences in observed cow performance amongst systems were embedded in the FU. The GHG efficiency of LFC was noted from rank analysis to be more favourable than that of the higher yielding LFS system. As reported in chapter 3 of this thesis, the Select genetic line animals were estimated to have higher feed and ME intake, and greater milk yield than Control line. This led to Select line having higher enteric methane emissions per cow and higher gross emissions associated with both forage produced on-farm and purchased feeds. However, unlike using ECM as the reference for emissions intensity, the higher gross emissions associated under Select line were not sufficiently offset by the higher productivity with this FU. In this respect, employing LU as the FU may thus provide a useful assessment of the true efficiency of dairy production systems. Livestock units have not been widely employed in studies, however, largely because LCA stipulates that the results of a study at systems level should be referenced to a unit of product output, or at least a generally accepted sales quantity (BSI, 2011). Although not considered appropriate as the sole FU for LCA of dairy production systems, LU does present a useful tool to compare the relative GHG emissions intensity of systems.

#### *4.4.1.2 Energy corrected milk*

Milk yields corrected for fat and protein content are the most commonly applied FU in LCA studies of dairy production. Employing ECM as a FU incorporated the effect of disparity in milk production amongst systems when examining the GWP. This was also the only FU to find the GWP of all four Langhill systems to be significantly different from each other. The LFS system was found to be the most efficient with respect to GWP per unit ECM. In a recent study based in Ireland, O’Brien et al. (2012) found that a confinement system was less efficient than a grazing system per unit corrected milk yield. The results of the present study contrast the findings of

O'Brien et al., but there were several differences in farm management practices and methods between the studies. Milk yields from the Irish systems were substantially lower than those of the Langhill systems. A further key difference was that, aside from grass, the majority of feed components of the Irish diets were purchased, and in many instances internationally imported. These included maize from the USA, rapeseed meal and beet pulp imported from Germany, palm kernel oil from Malaysia and soyabean meal from Brazil. Soya and palm oil in particular held very high emissions coefficients in calculations, in part because they included an account of emissions associated with land use change (LUC) related to conversion of rainforest or rangeland to arable land. In the Langhill systems, forage crops such as maize and wheat alkalage were grown on-farm, and the purchased components of the Langhill rations were largely sourced within Scotland/UK. Internationally sourced soyabean meal, made up only a small proportion of the Langhill systems' TMR. In a key methodological difference, the present study did not account for emissions associated with LUC relating to the imported soya cultivation. Therefore not only did soya meal comprise a greater proportion of the Irish feed rations, but the associated estimated GHG were also considerably higher. Langhill rations also contained a high proportion of by-products from the distilling and brewing industries, thus emissions associated with imported feeds were further lowered for Langhill systems compared to the Irish study. The off-farm contribution to the overall GWP of the High Forage systems (26%) was comparable with that for the Irish seasonal grass-based system (24%). However, the Irish confinement system attributed 45% of its overall GWP to off-farm sources, owing to high environmental cost associated with production of imported feeds. This compared to just 29% of the total GWP attributed to off-farm emissions in the Langhill Low Forage systems. All of these factors contributed to the relative ranking of the dairy production systems' GWP per unit ECM observed in the respective studies. This point serves to highlight the importance of examining methods and farm management practices when drawing comparisons between LCA studies which employ a common FU.

The crucial point when evaluating the environmental efficiency of dairy production systems is that ECM as a FU enables comparison of the relative balance of, and not the absolute or gross levels of pollution and production. In the present study, LFS

produced both the highest milk yield and highest gross GHG emissions relative to the other Langhill systems. However, estimated emissions associated with Low Forage regime purchased feeds were moderately low compared to what they might have been without benefiting from including by-products in the ration composition. Thus the relative balance of the two output quantities was lowest for LFS, and LFS was found to be the most efficient system in terms of GWP per unit ECM. In the Irish study, O'Brien et al. (2012) found that the confinement system was both the highest polluting system and highest producing. However, the balance of emissions and milk yield from the grazing system was found to be more favourable. Despite the relatively low milk yield, the Irish grazing system emitted lower levels of GHG to produce the same quantity of product milk. The contrasting results of these two studies highlight the strength of ECM as a FU for assessing GWP, and also the importance of understanding differences in methods and management practices between what might appear to be fundamentally similar studies and production systems.

#### *4.4.1.3 Milk solids*

Milk solids are another unit commonly used in the dairy industry, for example to compare the biological or production efficiency of cows, but seldom used in LCA. This is likely due to the fact that most dairy LCA studies have had their boundary drawn at the farm gate, and the principle product at that point being liquid milk. Exceptions to this have occurred in studies from countries where output of alternative dairy products including dried milk, whey powder and butter, is greater than liquid milk, such as New Zealand or Ireland (Saunders and Barber, 2007; O'Brien et al., 2011). For studies interested in the life cycle of dairy-derived products such as yoghurt or cheese, referencing the GWP to milk solids may also be more appropriate. Given the results obtained using ECM as the FU it was not unexpected that results from another unit of dairy production (MS) followed a similar trend, with LFS found to be the most efficient system and HFC the least. However, unlike using the corrected milk yield unit, there was no difference observed in GWP per kg milk solids between LFC and HFS. This was likely due to a confounding effect introduced by the interaction of forage regime and genetic line in the production systems. Both the fat and protein content of the milk were higher in systems managed under the

High Forage regime, while milk yields were elevated by the Low Forage regime. This was not unexpected, as cows managed on a Low forage diet have historically been subject to milk-fat depression, or low milk-fat syndrome (Bauman and Grinari, 2001). Both the milk yield and milk solids were increased with the Select genetic line, consistent with the potential of the Select genetic merit. Thus while the LFC system yielded a greater quantity of raw milk, it contained comparatively less milk solids, and HFS produced comparatively less milk but containing a higher proportion of solids. Although ECM incorporated a correction for the differences amongst systems' milk fat and protein content, the impact of this confounding effect upon the GWP results was more pronounced when milk solids was the FU. This emphasises the importance of considering not just the GWP result presented, but also what information the FU may contain, or tell us about the dairy production systems being examined. A further point to consider for this FU is that of comparability, not only with other LCA studies, but with other measures of efficiency. In chapter 2 of this thesis, one measure considered for the biological efficiency of the Langhill systems was the net energy required to produce a kilogram of milk solids ( $NE_{in}/MS$ ). By employing milk solids as the FU, this would enable direct and simple comparison of the biological and environmental efficiency of dairy production systems. This is an important point, as the two definitions of efficiency should not be considered in isolation when assessing the overall future sustainability of a dairy production system.

#### *4.4.1.4 Land use*

Employing land-use as the FU satisfies a conventional definition of efficiency as a measure of a system output versus an input. Further, land area conforms to ISO:14040 stipulation of the FU being a clearly defined and measurable reference to which input and output data are normalised (ISO, 2006). For studies which intend to inform national GHG inventory reporting, it is also necessary to choose a FU coupled with land for area based processes (IPCC, 2006). In agriculture this may include emissions associated with applied fertilisers, crop production and residues, but it is not a requirement for animal emissions such as enteric  $CH_4$ . The LCA process may include within its boundary emissions sources beyond those required for national inventory reporting, thus an area based unit is not a specific requirement of

LCA. Many LCA studies have variously referenced GWP to the on-farm grassland, on-farm combined pasture and forage crop land, or to the total on- and off-farm land, including that required for the production of imported concentrated feeds and bedding. In the present study, on-farm land was the only FU to find both systems under High Forage regime to be more efficient than both Low Forage systems. High overall GWP combined with lower on-farm land use through the absence of grazing meant that systems under the Low Forage regime were estimated to have comparatively high GWP per hectare of on-farm land. Under High Forage regime, the high on-farm land use resulted in the grazing systems appearing more favourable. From a LCA point of view, on-farm grassland area is not appropriate for examining results since relevant arable land, which could be located worldwide, should also be responsible for the environmental impact from the milk production on-farm (Yan et al., 2011).

Using the total land-use as the FU, the balance of results compared to those from the on-farm land-use FU was reversed. Both of the systems under Low Forage regime appeared more favourable in terms of GWP per hectare total land use. This can be attributed to the much higher estimated off-farm land associated with Low Forage regime. Furthermore, off-farm emissions were lower than they might have been, owing to the inclusion of by-products in the ration. There was no difference between two systems with different genetic line under the same forage regime using either of the land-based FU. Thus the effect of incorporating genetic lines selected for high productivity was nullified by a FU (either  $\text{Land}_{\text{farm}}$  or  $\text{Land}_{\text{total}}$ ) which did not distinguish between high and low productivity. Steinfeld et al. (2006) stated that improving productivity of livestock through improving genetic merit is one of the most promising approaches for reducing global emissions from livestock systems. It is perhaps a concern therefore, that if employing a land-based FU, a study may be unable to discern the benefit of a genetically improved, more production efficient system. This highlights a question of whether FU selection should be tailored to the intention of a study. Where a study seeks to compare the GHG efficiency of dairy production systems, the FU must be capable of reflecting any advances made in production efficiency. However, this is an entirely different goal to where the

intention is simply to inform of GHG emissions at a specified level, and in such an instance a land-based FU can be considered suitable for the purpose.

Casey and Holden (2005b) stated that the GWP per ha could be minimised through farm management, implementing low stocking rates. The current results agree with Casey and Holden, as a lower stocking rate would necessitate fewer cows (and their associated GHG emissions) occupying the same area, or a greater area of pasture to serve the same number of cows. In either case this would lower the GWP per hectare, and thus enhance the perceived efficiency of the grazing High Forage systems compared to Low Forage. However, lowering the stocking rate to this end presents a paradox, whereby the improved environmental efficiency of the dairy production system per hectare will arise through less efficient grazing of pasture. O'Brien et al. (2012) also noted that due to high productivity of temperate grasslands, a grazing system may appear less efficient per hectare. This notion can be extended to consider an example of a farm maximising forage crop yields, and thus requiring less land on-farm to produce feed for the dairy herd when housed. This increase in cropping efficiency would result in a smaller value for the land-based FU, making the system appear less favourable than before with respect to GWP per hectare. It must be considered impractical and counter-productive that improvement in efficiency of pasture and forage crop productivity, and thus greater efficiency of land-use, result in a less favourable perception of the environmental efficiency.

Another issue to address for area-based FU is that of equivalence between dairy production systems, both internationally and nationally. The land-use FU are simply measures of area, and cannot give account of what is inside that area. Countries or regions will differ considerably in terms of, for example, their management preferences, predominant climatic conditions, soil types, and availability or feasibility of crops. Brockman and Wilkins (1995) described variation amongst different species of grass in terms of their growth patterns, nutritional content, response to nitrogen, climate, and most importantly, potential difference in yields. In turn this will influence the range of animal breeds and management systems available to the dairy farmer, as well as the environmental impacts associated with them. In the present study all four Langhill systems were situated within, and sourced

forages from, the same farm, therefore GWP per hectare on-farm land was directly comparable. Saunders and Barber (2007), however, compared the life cycle of typical dairy production in New Zealand with that in the UK, expressing the total GWP per hectare. The purpose of a FU was noted earlier to serve as measurable reference to which input and output data are normalised. In the case of production based FUs, milk yields were able to be adjusted relative to their fat and protein content to ensure functional equivalence. In order to employ an area-based FU, an adjustment must therefore be made to ensure that a hectare of land in one region is comparable to a hectare of land in another. In a study comparing the production of wheat by different farming systems between the UK and Switzerland, Audsley et al. (1996) noted the very different areas of land used to produce equivalent quantities of grain. Land area was made equivalent amongst the three systems by assuming that the difference in land used was managed as set-aside land (Audsley et al., 1996). An earlier study by Moxey et al. (1995) developed a model for estimating crop yields based upon different land classes in the UK.

The issue of equivalence is further complicated when the FU incorporates the land-use required for the external production of purchased feeds. As noted earlier, the Irish dairy farm study by O'Brien et al. (2012) sourced maize grain and gluten from the USA, where maize yields are typically higher than those found in Europe (USDA, 2012). Thus the reported GWP of dairy production per hectare of total land-use may become inexorably linked to the efficiency of crop production abroad. This is especially important for systems which have a large purchased component of their diet, such as the Low Forage systems in the present study. Wackernagel and Rees (1996) introduced the notion of a 'global hectare' with their concept of the Ecological Footprint. The solution to equivalence was to quantify demand on biological resources by expressing all components of an impact as an equivalent land and sea area with world average productivity (Wackernagel and Rees, 1996). Yield factors were used in conjunction with equivalence factors to convert the actual physical area in local hectares into global hectares. Scaled down to agricultural systems level, the yield factors, obtained by dividing the local yield of a biological product by its global average yield (Weidman and Lenzen, 2007), can account for discrepancies between countries in productivity of a given crop and land type.



The present study also raised an issue of international equivalence, as the TMR for Low Forage regime included soyabean meal from Brazil. Although land-use associated with soya was accounted for in the present study, the Low Forage systems would likely have not been able to provide sufficient protein to maintain the level of their observed high productivity with domestically produced feed from an equal land area. However, this last point also serves as a reminder that the primary purpose of dairy production systems is to output milk. With appropriate account of crop yield and land-use equivalence made, an area based FU would be useful tool to reference GHG emissions, but interpreting the results of LCA of dairy production systems needs to incorporate a measure of productivity in the FU.

#### *4.4.1.5 Dual functional unit*

Godfray et al. (2010) stated that in modern global agriculture there is a pressing need for ‘sustainable intensification’, in which yields are increased without adverse environmental impact and without the cultivation of more land. To comply with this definition, it would be perhaps advantageous for LCA of dairy production systems to employ a FU which could account for all three of these criteria simultaneously – yields, GHG emissions and land-use. The proposed new functional unit in the present study aimed to account for both the productivity and the total on- and off-farm land use of a system. Despite LFS having significantly lower GWP per unit ECM, when employing  $\text{ECM}/\text{Land}_{\text{total}}$  as the FU there was no significant difference between the estimated GWP for LFC and LFS. Indeed, much like the two land-use based FU, there was no significant difference found between two systems under the same forage regime. It was perhaps surprising that the dual FU was able to differentiate only between the environmental efficiencies of different feeding regimes but not genetic lines, given the range of milk yields present amongst the Langhill systems. Despite accounting for milk yield, the FU did not reflect the difference amongst systems’ GWP that the existing FU incorporating productivity were able to determine. Furthermore, the balance of GWP and differences reported by the dual FU were not found to be dissimilar to that obtained by the total land-use unit. However, when analysing the systems’ relative efficiency rankings in the present study, the dual FU did find LFS to be significantly lower GWP than LFC, and thus

the most GHG efficient system. Hayashi (2013) described ‘trade-off conversions’ in impacts per unit land and per unit product, when assessing a switch from one production system to another. This trade-off saw improvement in one criterion being accompanied by deterioration of the other, and the study stated that occurrence of a win-win situation where improvement was observed in both criteria was rare (Hayashi, 2013). In the context of the dual FU, an improvement in GWP would be observed in either the win-win scenario, or a trade-off conversion with positive outcome. Thus the remaining scenarios - trade-off with negative outcome, and lose-lose scenario – would reflect an increase in GWP per the dual FU. The present study therefore shows that a dual FU, satisfying the inclusion of both production and land-use together, could be usefully employed to assess the environmental efficiency of dairy production systems. However, it must be approached carefully with consideration of the underlying changes both in emissions per land unit and product unit individually. Without this consideration the application of a dual FU could obscure fundamental and opposite effects of the systems’ efficiency of land use and production.

#### 4.4.2 A combined approach

The LFS system was observed in the present study to be the most efficient system with respect to GWP per kg ECM and one of two systems favoured per hectare of total land-use. The results of this study therefore support the statement of Yan et al. (2011), that a low GWP per kg productivity does not necessarily equate to a high GWP per hectare, and vice versa. It has also been noted in the literature that there is a lack of significant correlation between GWP per unit milk and GWP per unit land (Casey and Holden 2005b) owing to the trade-offs described by Hayashi (2013). An alternative explanation was presented by Yan et al. (2011), that one must consider the milk yield per cow, the stocking rate and ratio of on-farm to off-farm land use when equating GWP per ECM to GWP per total ha.

Casey and Holden (2005b) also stated that to identify the optimal dairy production system it is necessary to examine GWP referenced to both productivity and land based measures. Basset-Mens et al. (2009a) noted that it is necessary to select FU related to the key functions of the system, and not simply as a default unit. Thus assessment of the production function of a system would necessitate employing a FU

such as milk yield, and assessing the land-use function of a system requires an area unit. Thus to determine the optimal system in the present study, it was necessary to reconsider the LFC and LFS systems. Both were found to be jointly the most efficient when employing Land<sub>total</sub> as the FU. LFS was found to have the lowest GWP per kg ECM, with annual productivity estimated to be 16% higher in LFS than LFC. Therefore it can be concluded that in the present study the LFS was favoured in terms of GHG emissions intensity after taking account of both productivity and total land use measures. This system was also favoured by the dual FU after considering both the estimated environmental efficiency and relative ranking of the dairy production system.

Haas et al (2001) suggested that agricultural environmental impacts on a regional or local level, such as eutrophication or groundwater contamination, have a strong area-related aspect, therefore land was the appropriate unit of reference. However, a product-related FU was suggested to be more appropriate for environmental impacts such as GWP, which contribute on a global scale (Haas et al., 2001). The results of the present study agree that productivity, and corrected milk yield in particular, is the most suitable FU with which to interpret LCA in respect of GWP of dairy production systems. Nevertheless, the present study also agrees with the suggestion of Casey and Holden (2005b) and Basset-Mens et al. (2009a) - that examining the GWP referenced against both total land use and productivity separately will permit a more balanced appraisal of environmental efficiency. Furthermore, although the proposed dual FU did not find significant difference between the GWP of the two most efficient Low Forage systems in the present study, the unit ECM/Land<sub>total</sub> did display a degree of merit. The dual FU yielded results broadly consistent with both ECM and total land-use in the present study, and could help to assess the likelihood of a positive trade-off conversion between GHG emissions and efficiencies of land use and production.

#### 4.5 Conclusions

This life cycle assessment study indicated that the perceived environmental efficiency of different dairy production systems in terms of their global warming

potential was susceptible to change based upon the functional unit employed. Energy corrected milk was the most effective functional unit for reflecting differences between the systems. Functional units which incorporated a land related aspect could not find difference between systems which were managed under the same forage regime, despite their being comprised of different genetic lines with considerably different productivity. Corrected livestock units were found to be a useful functional unit for comparing the relative emissions intensity between systems, though not suitable to be the sole unit for a study. Employing on-farm land as the functional unit was found to favour grazing systems, but this did not accurately reflect the wider boundary of the life cycle of dairy production beyond the farm. Combined total on- and off-farm land use was found to be of merit, however this functional unit should be interpreted carefully by decision makers if being employed as the singular unit of reference for analysis. A proposed dual functional unit combining both productivity and land-use did not differentiate between emissions intensity of systems as effectively as the productivity based units. However this dual unit displayed potential to quantify in a simple measure the positive or negative outcome of trade-off conversions between land and production efficiencies. This unit should nevertheless be treated with the same caution as all standalone FU, and consider in context with the underlying individual effects of land and production based units so as to not overlook any confounding effects between the two functions.

The results from LCA of dairy production systems should be considered in context with the methods and management practices in order to make an informed appraisal of the information presented by the functional unit. This study concludes that energy corrected milk yields should remain the primary functional unit for interpretation of the life cycle analysis of a dairy production system, but combined land use and a dual FU should be employed in a secondary role in order to present a balanced analysis.

## **Chapter Five**

## **Chapter Five**

### **General Discussion and Conclusions**

#### **5.1 Introduction**

Under the terms of the Kyoto Protocol, nations across the world entered binding commitments to decrease greenhouse gas (GHG) emissions in order to mitigate against future climate change. Livestock production contributes approximately 18% of the world's total GHG emissions, and the sector is predicted to double production by 2050 (Steinfeld et al., 2006). If the dairy industry is to continue to meet demand for dairy products, ways to minimise GHG emissions in a sustainable way will become increasingly important. Over the last century, intensification of agriculture introduced significant changes to farming practices. The efficiency of dairy production saw improvement through advances in animal breeding, nutrition and management, and this has been accompanied by associated improvement in environmental efficiency (Capper et al., 2009). However, in order to meet the climate change policy targets, such as those stipulated in the Climate Change (Scotland) Bill (Scottish Government, 2009a), further advances are necessary. It is therefore important to investigate ways to further improve the efficiency of dairy production systems and at the same time to minimise their global warming potential (GWP). Improvements in dairy cow genetics and animal management system are estimated to represent both real and cost effective GHG mitigation measures (Eory et al., 2013).

The aim of this research project was to investigate the effect of improving the genetic composition of the dairy herd, combined with different feed and management systems, on the biological and environmental efficiencies of dairy production systems. Two feeding regimes (low forage (LF) and high forage (HF)) were applied to each of two genetic lines (control (C) and select (S) genetic merit for milk fat plus protein) giving four contrasting dairy production systems (LFC, LFS, HFC, HFS). Mitigation strategies for the environmental impacts in this research were considered at production system level. This ensured that reductions in one part of a system did not stimulate associated higher emissions in another (de Klien and Eckard, 2008), and enabled the most efficient dairy production system to be identified.

## 5.2 Consolidation of research

### 5.2.1 Animal performance and biological efficiency

While the main aim of this research project was to identify the most efficient dairy production system with respect to greenhouse gas emissions, it was first necessary to examine the systems' performance and biological efficiency. This project cannot draw conclusions and recommend a production system as optimal, without first considering the productivity and future sustainability of each system.

The current study has shown that the production system with select genetic line under low forage regime (LFS) had the highest gross production and energetic efficiencies. It was not unexpected that animals of the Select genetic line would be more productive, being selected for their genetic potential for milk production. However, despite the historical improvements in efficiency of dairy production noted by Capper et al. (2009), this clearly demonstrated the potential that exists within the Holstein Friesian cow to further improve biological efficiency through breeding and feeding strategies. Cows of the LFS system were found to allocate the highest proportion of their net body energy to lactating after accounting for body maintenance. Previous studies have shown that body energy allocation to milk production is maximised in a cow selected for production and maintained on a high concentrate or low grazing diet (Veerkamp et al., 1994; Coffey et al., 2004). Dillon et al. (2006) stated that larger North American strain of Holstein-Friesian cows, such as those in the present study, show a better response in milk yield with a higher proportion of concentrate in their diet, than smaller genotypes. This is consistent with the findings of O'Brien et al. (2011), who noted that milk yields from the smaller New Zealand strain of Holstein-Friesian cow did not increase significantly when switched from a fully grass-based system to a high concentrate diet.

Although estimating the biological efficiency of dairy cows is common in published research, the present study showed the differences in the rate of change in biological energetic efficiency over the course of a lactation, occurring within a breed and as a

result of management. In a study assessing feed efficiency of dairy cattle, Coleman et al. (2010) noted that although there were differences between strains of Holstein-Friesian, there was also variation in efficiency within a genotype. Veerkamp et al. (1995) examined the gross body energy of cows throughout lactation, and found that Select genetic merit were the most energetically efficient, while a high or low concentrate diet was not significant. In the present study, as lactation progressed, cows of all systems were found to lose energetic efficiency, however the rate of this loss was different amongst systems. The rate of change in energetic efficiency was lowest in LFS and very high in HFC. Thus not only was Select genetic line managed under Low forage regime the highest producing and most biologically efficient of the four systems, but the margin of its superiority in these categories over the other systems actually increased during the course of lactation. Thus despite the large scale advances already achieved over the past century, this demonstrates the significant potential remaining within the Holstein-Friesian breed to improve efficiency of production.

#### 5.2.2 Environmental efficiency

Environmental efficiency was defined as the lowest emissions intensity, minimising GHG emissions per functional unit. Employing life cycle assessment (LCA), the LFS system was found to be the most environmentally efficient dairy production system with respect to GHG per unit of energy corrected milk (ECM), and HFC the least. Implementing the low forage regime with select genetic line lowered GWP per kilogram of energy corrected milk (ECM) by 24% compared to HFC. The results therefore demonstrate that LFS production system was found to be the most environmentally efficient in addition to the most biologically efficient system in this study. This supports the statement of Capper et al. (2009), who noted that improvement in production efficiency of dairy systems is historically accompanied by associated improvement in environmental efficiency.

Casey and Holden (2005b) stated that reducing farm emissions could be achieved by maximising the productivity of a dairy herd, thus operating with fewer cows and their associated pollution in order to obtain the same milk yields. The present study



has demonstrated LFS to be of the highest production efficiency, and this was crucial in offsetting the high overall emissions produced at system level. Studies have previously also found LFS to be the most environmentally efficient system at cow level, with respect to enteric CH<sub>4</sub> and excreted non-milk nitrogen per unit productivity (Bell et al., 2009; Chagunda et al., 2009). In these studies high overall emissions were also found to be balanced by high productivity. There were several further reasons for this particular system to have also stood out as the most environmentally efficient in the present study. Key factors in the differences amongst systems were higher off-farm GHG emissions under low forage, and higher on-farm nitrous oxide (N<sub>2</sub>O) emissions under high forage regime. The absence of grazing in Low forage groups resulted in lower N<sub>2</sub>O emissions brought about through lower requirement for manufactured fertiliser use, and no direct deposition of manure at pasture. Further, the use of distillery by-product grains in the purchased element of low forage feeding ration enabled the environmental cost of feed production to be minimised and reduced the on-farm land requirement. HFC produced 91% more N<sub>2</sub>O per kg ECM from animal manures compared to LFS, and 65% more N<sub>2</sub>O from applied manufactured fertilisers. Conversely, GWP associated with off-farm production of imported feeds in LFS was 11% higher than in HFC. Productivity did play a significant role, however, as Low forage systems' high gross emissions were offset by high milk yield, but this was not the case for the high forage systems.

### 5.2.3 Future sustainability of the identified leading system

The current study has clearly identified that cows of the select genetic line managed under low forage regime was the most biologically efficient and environmentally efficient system under the measures of efficiency employed in this study. However, examination of animal performance traits raised a serious question of concern regarding the sustainability of LFS system. The involuntary culling rate in LFS was significantly higher than that observed in the other systems. Any further increase in involuntary culling rate would begin to inhibit the ability of LFS cows to raise sufficient replacement heifers. There is an established negative association between genetic selection for productivity and traits for reproduction and animal health (Pryce et al., 1999; Veerkamp et al., 2001). Further, it has been observed that animals

selected for high productivity do not replenish all of their body reserves which were mobilised in early lactation (Coffey et al., 2004). This probably explains how LFS is able to maintain its extremely high rate of energetic efficiency right throughout lactation, as the animals were predisposed to continue prioritising production over other traits. As lactation progressed, cows in other systems appear to have reduced energetic efficiency in order to divert energy back into replacing reserves. Although displaying a small drop in energetic efficiency, LFS animals meanwhile diverged further from the other systems, continuing high productivity even to their own detriment. Thus the superior production performance and biological efficiency exhibited by LFS may come at the expense of the future sustainability of the production system.

In a previous study, Chiumia et al. (2013) noted that the main reasons for culling multiparous cows from Langhill were fertility and udder problems, whilst the majority of 1<sup>st</sup> lactation heifers were culled for fertility reasons alone. It was therefore assumed that fertility was the principle issue underlying the high involuntary culling rate in the present study. It has been proposed that future genetic selection indices should place higher emphasis on fertility (Royal et al., 2002), therefore developing the ability to select animals that can cope with increasing levels of milk production while avoiding undesired culling for reproductive failure. Studies have shown, however, that the estimated heritability of fertility traits is low (Weigel et al., 2006; Menendez-Buxadera et al., 2013) and that genetic improvement of fertility is generally negatively associated with improved productivity (Wall et al., 2003). It has also been suggested that the fertility of a dairy herd could be improved through nutritional strategies (Garnsworthy and Webb, 1999). Feeding a diet designed to increase their insulin status was found by Gong et al. (2002) to have a beneficial effect on dairy cows fertility. It was noted by Garnsworthy (2008) that such nutritional strategies, likely to contain a high proportion of maize and concentrates, would be complementary to dietary strategies already proposed to mitigate GHG emissions. This point is particularly pertinent to a zero-grazing, low forage feeding and management system such as that in the present study, where cows feed intake is controlled through a total mixed ration. Garnsworthy (2008) also estimated that if dairy cow fertility could be restored to 1995 levels, there would be

an associated reduction in CH<sub>4</sub> and ammonia emissions of 11% and 9% respectively, owing to reduced requirement for rearing of replacement animals. The real-world effectiveness of both of these strategies would require substantial time to investigate, constrained by the natural length of the reproductive cycle. These ideas do however merit future research, and could prove to be essential to the sustainability of high producing dairy production systems. The present study has demonstrated the considerable potential remaining in such dairy production systems to improve productivity and biological efficiency, but this should not be considered exclusive of cows' reproductive concerns.

#### 5.2.4 Experimental constraints

One of the aims of this project was to conduct the LCA using system specific data and coefficients, in order to truly define differences amongst the four dairy production systems. The LCA method is well established for the dairy sector, and this study benefited from access to the extensive and detailed farm data recorded in the unique Langhill database. However, within the confines of a retrospective desktop study, this project was not without methodological constraints. Comprehensive and system-specific data were available on, for example, milk yield and composition, animal performance traits, feed intakes and ration formulation. Further, data such as fuel use was detailed for every daily farm activity. However, for practical reasons, data such as rates of nitrogen volatilisation and leaching from pasture were not available retrospectively, and indeed could not have been recorded to the same level of historical detail. Therefore, when it came to conducting impact assessment, calculating emissions of N<sub>2</sub>O in particular, the study employed coefficients and emissions factors provided by Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006). However, the IPCC coefficients employed in calculations are well established in LCA. As noted earlier, the absence of grazing land, its associated manufactured fertiliser application, and of any animal manures deposited at pasture were key differences between the Low and High forage management regimes. The present study would, therefore, have benefitted further from Tier 3 data for N<sub>2</sub>O emissions in order to fully quantify specific differences amongst production systems.

The efficiency of farm management practices which were already in effect at Crichton Royal Farm (CRF) represent a further methodological constraint and caveat which must be considered before attempting to when interpreting results for GWP from the LCA. Over the study period, CRF operated an organic fertiliser management practice of implementing slurry injection. This practice enabled a reduction in the rate of manufactured fertilisers required, whereby nitrogen application rates during the study period were 40% lower than previously at CRF (Ross et al., 2011). Misselbrook et al. (2002) found that shallow injection reduced ammonia emissions by up to 73% compared to surface application, however studies have noted there is an associated increase in N<sub>2</sub>O emissions (Flessa and Beese, 2000; Velthof and Mosquera, 2011). Jarvis (1996) stated that a tactical approach to fertiliser application and slurry injection could reduce nitrogen losses in the field by up to 46%. As noted earlier, it was not possible to quantify precisely the actual level of emissions from the injected slurry, therefore standard emissions factors were used in calculations regarding application of animal manures to the field. This therefore represents a potential overestimate in the level of the GHG emissions from applied organic manure. However, a benefit in the form of reduced manufactured fertiliser application was reflected in the LCA calculations, therefore estimated GWP of all systems was lower than perhaps would have been observed on a farm with different strategy for application of organic and manufactured fertilisers.

Audsley et al. (1997) stated that allocation of environmental effects to the different functions delivered by a multi-function system was a fundamental problem in LCA. The allocation of emissions therefore represents a further potential point of difference in the thesis. Allocations amongst co-products were made for both purchased feeds brought onto the farm, and between co-products milk and meat leaving the farm. Purchased feeds, for example rapeseed meal, were separated in the analysis based on the allocation values used by Cederberg and Mattsson (2000), which were similarly employed by Bell et al. (2011). The order of preference stated by Audsley et al. (1997) was: system expansion, physical/biological causality, composition and mass allocation, and economic allocation. Two of these options – mass allocation and economic allocation – were presented by Cederberg and

Mattsson (2000), displaying notably different allocation values between them. Emissions associated with oilseed rape, for example, were divided between oil and meal 60:40 by mass allocation, but 67:33 in the case of economic allocation. The selection of economic allocation values thus allocated a smaller proportion of emissions to the rapeseed meal co-product than mass allocation would have done. Similarly, the allocation of soybean meal emissions (allocation 80% by mass, 69% by economic) and sugarbeet molasses (12% by mass, 6% by economic) were also more favourable using the economic method. This thesis employed the higher mass allocation values, stated as higher in order of preference by Audsley (1997), thus the estimated GWP for each dairy production system could actually have been lower than presented in the thesis had the economic allocation been adopted instead. Division of emissions between outputs milk and meat were also separated based on mass allocation, following the reasons outlined in the LCA methods in chapter 3 and using the methods of the IDF (2010). The average allocation value to product milk was determined as 83%, 88%, 81%, 87% for LFC, LFS, HFC, HFS systems respectively. However, studies in the literature have often employed an economic value of 85% allocated to milk (including: Cederberg and Mattsson, 2000; Basset-Mens et al., 2005; Saunders and Barber, 2007), and the IDF state a default value of 85.9% to milk (IDF, 2010). In this thesis, the allocation to milk in the two Select systems was therefore slightly higher than the given economic value, reflecting the greater milk production of the Select genetic line. Applying the default economic value would thus have further reduced the estimated the GWP of Select systems, while slightly increasing the estimated GWP of systems with the Control line. Employing system expansion, the preferred option in the hierarchy of allocation methods, the environmental burden of the first year and a half spent raising sold livestock is assigned to the beef industry. Cederberg and Stadig (2003) estimated that employing allocation via system expansion would have allocated more than a third of the estimated climate change impacts to product meat. This allocation method would have likely lowered the estimated emissions intensity of all four systems even further, and highlights the difficulties faced when comparing the results of studies which have employed different methods.

### 5.3 Practical implications

#### 5.3.1 Potential real reduction in Global Warming Potential

The Scottish Climate Change Delivery Plan (Scottish Government, 2009b) set the agricultural sector a target to reduce emissions by 1.3 Mt CO<sub>2</sub>e by 2020, equivalent to a 42% reduction. The dairy sector was not charged with a specific individual target under the plan, although the large scale of emissions means that dairy production systems will play a major role contributing towards attaining the government's ambitious climate change targets. The current study aimed to anticipate the level of environmental gains which might be observed if the dairy industry were to adopt the leading system. However, it would be overly simplistic and unreasonable to take the levels of GHG emissions estimated for the leading dairy production system from LCA and apply them at a national level. That would rely on an assumption that every dairy farm in the country will endorse and apply the LFS system, which likely is neither practical nor realistic. What the results of the present study do quantify is the scale of the potential that exists within Scottish and UK conventional dairy production systems to mitigate GHG through genetic selection and implementing different feed and management systems.

The average annual yield of raw milk per cow from HFC system in this study was comparable with the estimated British national average milk yield over the same period (DairyCo, 2012b). Further, the Control line was maintained to be of average national genetic merit, and High forage cows were managed in a conventional forage and grazing regime. HFC therefore serves as a reasonable baseline as an average Scottish system for the results of this study. The LCA results estimated that implementing the LFS system held the potential to reduce the GWP per unit milk by 24% compared to HFC. This represents mitigation potential for the dairy industry of more than half of the interim 2020 emissions reduction target should the LFS system be widely adopted. Further, Holstein-Friesian cows are estimated to account for 95% of the national dairy herd (Dairy Council, 2012), therefore results of the current study can be considered applicable to the majority of farms nationally. Adopting just one

of the mitigation measures examined in this study would also considerably reduce GHG at dairy farm level. Individually improving genetic merit and thus implementing HFS system was found to hold a potential GWP reduction of 9%. This improvement would be easier to put into operation as it requires little change to how the farming system operates. Similarly, switching to Low forage management regime, and thus implementing a LFC system, was found to hold potential GWP reduction of 17%. Both of these systems could also make substantial contributions to the government targets while simultaneously improving production. One cautionary caveat to consider is the method of carbon accounting employed by the government to estimate reductions may employ different emissions factors, such as those for enteric CH<sub>4</sub> in the present study, or different boundaries with a narrower scope than the LCA. In such a case the estimated saving in terms of GHG emissions may be less than the values estimated in this study.

A UK study by Jones et al. (2008) estimated that increased production efficiency, through genetic improvement in dairy cows alone, had reduced GWP per unit of milk by 16% between 1988 and 2007. Further, the study predicted that the improvement could continue at a rate of 0.5% reduction in GWP each year for 15 years if current selection practices continued (Jones et al., 2008). This equates to a potential 7.5% reduction in GWP by genetic improvement alone, and is broadly comparable with the 9% estimated potential reduction improvement from genetic merit from the present study. Studies have suggested that a figure of 50% represents a moderate assumption as to the potential uptake of mitigation measures by farmers (Vellinga et al., 2011; Kelly, 2012). Applying this figure to the results from the current study gives an estimated 12% reduction in the GWP of dairy production nationally, achievable by improving genetic merit and implementing a Low forage regime. Kelly (2012) estimated that moderate uptake of genetic improvement, combined with lengthening the grazing season and reducing nitrogen application through sowing of legumes, could reduce GWP of grazing systems by 16% by 2020 compared to 2008 levels. Vellinga et al. (2011) found that farmers preferred mitigation options in the Netherlands were to increase milk production per cow, use more maize in animal feeding, replace fed concentrates in the ration with by-products, and to reduce manufactured fertiliser input. It is notable that each of these mitigation options was

also a contributing part of the LFS system in the present study. The Dutch study estimated that implementing those measures, in addition to heat re-use from milk cooling, would provide reduction in GWP of dairy production of 8% at the moderate uptake level.

It was noted earlier that the strain of Holstein-Friesian cow was a factor in the response by milk yield to either a high or low concentrate diet. Basset-Mens et al. (2009a) found that, using the smaller New Zealand Holstein-Friesian cow, switching from a low input to a more intensive conventional dairy production system could increase GWP by 17%. In a different study, O'Brien et al (2010) showed that high producing North American Holstein-Friesians could reduce dairy production system GWP by approximately 6% when switching from a grass-based to high concentrate diet. When managed under the same two feeding regimes, animals of the New Zealand Holstein-Friesian strain displayed a slight increase in GWP when fed the high concentrate diet (O'Brien et al., 2010). These results suggest that strain of Holstein-Friesian is important, and that the level of environmental gains estimated for the Low forage production system might not be observed if employed to manage a herd of the smaller strain of cows.

### 5.3.2 Feasibility of implementing LFS production system nationally

The Select genetic line of the Langhill herd was representative of the top 5% of UK genetic merit for milk fat and protein production (Pryce et al., 1999), and continuously housed dairy production systems only comprise around 5% of the UK dairy industry (Wilkinson et al., 2011). The LFS system is therefore representative of a genetic and management regime which has so far rarely been implemented in UK commercial dairy herds. Genetic improvement is a relatively cost effective means by which to achieve reductions in GHG emissions, as the effect is cumulative and permanent (Bell et al., 2012). However, genetic improvement of the herd takes time and, depending on industry uptake, the effect on reducing GWP might not be widely observed in time for the interim target in 2020. The effects would, however, certainly be evident in time for the ultimate climate change reduction target in 2050. Switching to a low forage regime could be implemented quickly and provide an



instant mitigation against GHG as well as boost productivity. The LFC system was estimated to be the second most environmentally efficient system and still represented substantial production and environmental benefits in comparison to the summer grazing high forage systems.

As a consequence of adopting the Low forage regime, any dairy farm making the transition from a high forage regime will obtain a substantial amount of redundant on-farm land previously used as pasture for grazing. This land represents an opportunity to diversify and grow crops for use in animals' concentrated feeds, which will become increasingly important should there be an uptake in conversion of dairy production systems to a Low forage regime. Alternatively the extra land could be set aside for biodiversity management, or be used to further mitigate GHG through carbon sequestration. The Scottish government has set ambitious targets to afforest a further 650,000 hectares of land nationwide, requiring upwards of 10,000 hectares of land per year to be planted (Scottish Government, 2011). Incentives are available to grow energy crops such as short rotation coppice willow to sell for biomass power generation. Extra land might be tenanted as grassland to neighbouring farms, could be given over to arable farming, or perhaps used to grow wheat and maize to supply to upland farms also wishing to adopt a low forage regime. Additionally, the capture of 100% of animals' urine and manure from a continuous housing system presents opportunity to be capitalised upon by the installation of an anaerobic digestion (AD) facility. The estimated GHG abatement from AD is based on avoided  $\text{CH}_4$  emissions from animal manures, plus  $\text{CO}_2$  emissions avoided from displaced electricity generation (Moran et al., 2011). Vellinga et al. (2011) estimated that implementing AD held potential to reduce GWP of dairy production systems by 6% on its own. Furthermore, there remain many other measures which have been shown to provide real GHG mitigation, and are available to all conventional dairy production systems. These measures could include the use of nitrification inhibitors in the field, a more targeted use of organic and mineral fertilisers, and use of milk heat exchangers to heat water for the farm, reducing fossil fuel energy use. Integrating these measures along with the abatement potential of improving genetic merit and implementing a low forage regime demonstrated in the

present study, the ambitious government climate change targets appear attainable for the dairy sector.

A key factor in the GHG efficiency of Low forage regime was the sourcing of by-product grains for concentrate feeds from the Scottish distilling industry. DairyCo (2013) noted that use of such by-products in animal feeds has doubled over the past five years across the UK. This has led to growing concerns over the availability of by-products to Scottish farmers, owing to increased exports to England, increased price, and the use of grains for renewable energy as a feedstock for AD by the distilleries themselves (Bell et al., 2012). The lack of security in the future supply of by-products presents an obstacle to the Low forage regime becoming a more attractive and widely adopted system. A farm operating a Low forage regime would have to purchase and possibly import concentrated feeds from elsewhere at higher economic and environmental cost, or revert back to a High forage regime. However, the opening of new bioethanol processing plants in England in the past two years could offer a solution (DairyCo, 2013). At present Scottish distilleries are estimated to produce up to 466,000 tonnes of by-product grain per year on a dry matter basis (Bell et al., 2012). The recently opened bioethanol plants at Teeside and Hull hold the potential to produce 750,000 tonnes of grain for feeds, vastly exceeding the Scottish distillery output. Although the actual output from the bioethanol plants is hard to accurately predict, the future implications should include a reduction or cessation of Scottish exports to England, leading to greater availability and competitive pricing of by-products for Scottish farmers (Bell et al., 2012). This security of supply will improve the future viability and sustainability of the Low forage regime, perhaps even enabling a higher inclusion of by-products in the diet, and thus further reducing the off-farm GHG emissions.

Adoption of the low forage regime by farms will depend on being able to appropriately match the production system to their local environment, geography and predominant climate. Van der Werf et al. (2009) showed that while an intensive system may be more environmentally efficient than an extensive grazing system in one particular country, the opposite may be equally true for studies based in a different country. In the present study, the more intensive LFS system was found to

be the leading system, biologically and environmentally, for a farm situated in lowland environment. However, dairy farms in an upland environment, for example, may not be able to readily adopt such a feeding and management regime as they may be unable to grow forage maize and wheat alkalage. Maize, as an example, has not traditionally been grown in Scotland despite its advantages as a cattle feed. This is due to difficulties of its late season harvesting and the Scottish climate is generally unfavourable for commonly used varieties. However, new varieties have been developed that mature earlier and so are better suited to the climatic conditions of northern Europe (SNH, 2001). These developments have allowed the growing season to be reduced by 2-3 weeks, and the crops are also more cold tolerant, thus making maize growing in Scotland a more realistic proposition (SNH, 2001). According to 2012 June Census records there has been a four-fold increase in maize production for stock feeding since 2004 (Scottish Government, 2012), therefore interest in this component of the LFS system appears to have already been stimulated amongst Scottish dairy farmers. The addition or increase of maize in cows' diet has been shown to reduce enteric CH<sub>4</sub> emissions and increases milk production (Bell et al., 2012). However, ploughing grassland to grow maize may counteract these positive effects, as the loss of soil carbon and the loss of sequestration potential are much larger than the annual mitigation (Vellinga and Hoving, 2011). Van Middelaar et al. (2013) stated that a conversion of grassland to permanent maize cropping would require 44 years before emissions due to land use change were compensated. If grass-maize cropping rotations were maintained, it is estimated that annual increase in GWP owing to emissions of N<sub>2</sub>O would exceed mitigation indefinitely (Vellinga and Hoving, 2011).

Continuous housing of dairy cows, such as in the low forage regime, is rare in UK at present. Haskell et al. (2006) noted that this management practice is gaining in popularity, however, as cows with high genetic potential for milk yield can be fed high levels of concentrate more easily. Reijs et al. (2013) stated that grazing systems were in decline across all of Europe. Fully housed systems account for around 50% of dairy in Alpine regions of Europe (Wilkinson et al., 2011) but 0% in Sweden where at least two months grazing is mandatory under animal welfare law (Reijs et al., 2013). Continuous housing is particularly common in regions where grass is in

short supply, where the climate is unsuitable for growing grass or is too harsh for the animals to endure outside. An extreme example of this is the 37,000 cow “super dairy” at Al Safi in the Saudi Arabian desert. The increasing interest in housed systems in the UK has been accompanied by concerns about the welfare of the animals managed under them. It has been suggested that animals are prevented from expressing their natural behaviour and accessing natural surfaces, while the close proximity living can aid disease to spread quickly through a herd (POST, 2012). Furthermore it has been shown that housing cows throughout the year has a potentially detrimental effect on cows’ foot and leg health, although this may be alleviated through good free-stall design (Haskell et al., 2006). However, provided that animals are divided into appropriately sized groups and their needs managed by a high standard of stockmanship, large continuously housed dairy units offer a satisfactory standard of welfare for the dairy cow (FAWC, 2009; 2010).

#### 5.4 Conclusions

This study found that cows of high genetic merit managed under a Low forage feeding regime had improved production, energetic and environmental efficiencies. The rate of change in energetic efficiency over the course of lactation was found to differ amongst systems. The Low Forage Select system demonstrated the potential that exists within conventional Holstein-Friesian dairy production systems to improve milk yields and make a real contribution to reducing the global warming potential of the dairy sector. Through sensitivity analysis, this study identified the IPCC emissions factors contributing the most uncertainty to the global warming potentials estimated by way of Life Cycle Analysis. The perceived environmental efficiency of dairy production systems was shown to vary depending on the functional unit used, and energy corrected milk was determined to be the most appropriate functional unit.

Low Forage Select system was estimated to contain the potential to reduce global warming potential by 24%, thus making substantial contribution to attaining national greenhouse gas emissions reduction targets. Individually improving cows’ genetic merit and implementing Low forage regime held mitigation potential of 9% and 17% respectively. Issues with fertility and animal replacement raise questions about long

term sustainability of the LFS dairy production system, emphasising the importance of examining trade-offs between systems. Ways to restore fertility to high producing cows should be a priority for future research.

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## **Appendix**

## Effect of herd expansion and reduced inorganic fertiliser use on the global warming potential of four divergent dairy production systems

Ross, S.A., Chagunda, M.G.G., Topp, C.F.E. and Ennos, R.A

Abstract presented at *Advances in Animal Biosciences, Conference of the British Society of Animal Science and of Veterinary Teaching and Research Work. Jubilee Campus, Nottingham, UK, April 2011*

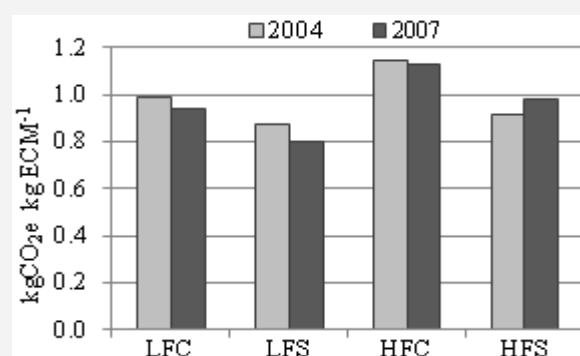
**Introduction** Dairy production is an important contributor of methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>), which are greenhouse gases identified by the IPCC (IPCC 2007). A substantial unavoidable component arises from natural biological processes; however, the high level of emissions opens up opportunities for mitigation. The majority of studies on Global Warming Potential (GWP) have examined dairy systems, or snapshots of a dairy system, at national and farm level. Analyses on the potential variation between production systems are sparse. The aim of the current study was to assess the impact of herd expansion and farm management practices on the GWP of four divergent dairy production systems using Life Cycle Analysis (LCA).

**Materials and Methods** Analysis was based on four dairy systems within Scottish Agricultural College's (SAC) long-term Holstein-Friesian genetic and management systems project at Crichton Royal Farm (CRF), Dumfries. Data for two contrasting calendar years were used, on two feeding regimes of high and low forage, and two genetic lines, Select and Control. High forage (HF) group had 75% of their diet from home grown crops (grass silage, maize, alkalage) with grazing outdoors when available. Low forage (LF) group were retained indoors all year round and were fed a diet of approximately 45-50% home grown feeds and the remainder sourced from imported concentrates. Select animals (S) represent the top 5% of UK genetic merit, determined by fat and protein content of milk production, while control animals (C) are of UK average genetic merit. This provided four divergent systems; LFS, LFC, HFS, and HFC and the two contrasting years were 2004 and 2007. The year 2004 was taken as a baseline because this was the full first calendar year after the herd had been established at CRF. In 2007 milking herd numbers had increased by 25% and non-milking stock increased by 39%, while grazing for high forage groups increased from 125 to 160 days. In addition, a 40% reduction in inorganic fertiliser application was achieved with the introduction of slurry injection. Implementation of LCA enabled accounting for the environmental impacts of the whole farm systems and their production of milk from 'cradle to the gate'. Inventory analysis was conducted analysing data on herd dynamics, milk yield and composition, feed intake, crop and land requirements, fertiliser and fuel use. System-specific coefficients were calculated for enteric CH<sub>4</sub>, excreted nitrogen and storage of animal wastes. Impact assessment was conducted using SAC Carbon Calculator, developed in line with IPCC and UK National Inventory guidelines (RBU 2009).

**Results** Between the two years, LFC, LFS and HFC displayed a significant increase in GWP ( $P < 0.05$ ), HFS was noted to increase 1% (Table 1). However, GWP per unit energy corrected milk (ECM) reduced in LFC, LFS and HFC but increased in HFS (Figure 1). Gross CO<sub>2</sub> emissions increased 49% and 46% for LFC and LFS respectively, while gross CH<sub>4</sub> emissions increased for all groups. Emissions of N<sub>2</sub>O increased 11% in LFC with no change for LFS, while HFC and HFS reduced 8% and 16% respectively. The results of the study showed that forage and genotype influenced the GWP of different dairy systems and that CH<sub>4</sub> emissions and farm productivity were key factors. Even with a 46-49% increase in CO<sub>2</sub> due to feed imports, the LF groups were more efficient in 2007. Despite an increase in outdoor grazing and lower N<sub>2</sub>O emissions due to reduced inorganic fertiliser use, the HF groups were still less efficient per unit milk than LF groups. Although gross emissions increased in all four systems, increased milk production in LF groups resulted in reduced GWP per unit energy corrected milk from 2004 to 2007 (Table 1).

**Table 1:** Systems total GWP and annual milk yield

	System	2004	s.d	2007	s.d	Δ%
Milk yield kg cow <sup>-1</sup> year <sup>-1</sup>	LFC	8385	2463	8976	2601	7%
	LFS	10271	2910	10406	2741	1%
	HFC	7375	2124	7299	1872	-1%
	HFS	8165	2345	7809	1944	-4%
GWP t CO <sub>2</sub> e	LFC	342.0		417.6		22%
	LFS	334.4		384.1		15%
	HFC	378.2		416.5		10%
	HFS	363.8		367.6		1%



**Figure 1:** Systems GWP per unit ECM

**Conclusions** As the productivity of intensive LF systems increased through herd expansion and milk yield per cow, their GWP per unit of product improved. The potential benefits of reduced inorganic fertiliser use to GWP were offset by an increase in enteric CH<sub>4</sub> and waste nitrogen due to increased herd numbers. This study is part of a long term analysis into the effect of forage type and genetic merit on the balance of GWP within dairy production systems.

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## Relative Carbon Efficiency of Four Divergent Dairy Production Systems

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*Abstract presented at Scottish Government Agriculture and Climate Change Workshop. Royal Botanic Gardens, Edinburgh, October 2011*

### **Summary**

Dairy production is an important contributor of methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>). Although a substantial unavoidable component arises from natural biological processes, the overall high level of emissions in dairy production opens up opportunities for mitigation. The majority of studies on Global Warming Potential (GWP) have examined dairy systems at national and farm level, or snapshots of a dairy system. Analyses on the potential of variation within a conventional production system are sparse. The aim of the current study was to assess the effect of interaction of forage and genotype on the GWP of four divergent dairy production systems within the same farm, using a partial Life Cycle Analysis (LCA).

Analysis was based on four dairy systems within Scottish Agricultural College's (SAC) long-term Holstein-Friesian genetic and management systems project at Crichton Royal Farm, Dumfries. Data covered a period of seven years (2004 to 2010), on two feeding regimes of high and low forage, and two genetic lines, Select and Control. High forage (HF) group had 75% of their diet from home grown crops (grass silage, maize, alkalage) with grazing pasture when available. Low forage (LF) group were fully housed and were fed a diet of approximately 45-50% home grown feeds and the remainder sourced from imported concentrates. Select animals (S) represent the top 5% of UK genetic merit, determined by fat and protein content of milk production, while control animals (C) are of UK average genetic merit. This provided four divergent systems; LFS, LFC, HFS, and HFC. All groups were milked three times daily, received equal treatment regarding health and fertility and all young stock were managed together. Implementation of LCA accounted for the environmental impacts of all system inputs and processes leading to product raw milk leaving the farm gate. Inventory analysis assessed herd dynamics, milk yield and composition, feed intake, cropping and land requirements, energy and fuel use, imported feed and fertiliser. System-specific coefficients were determined for enteric CH<sub>4</sub>, excreted nitrogen and storage of animal wastes. Impact assessment was conducted using SAC Carbon calculator, developed in line with PAS:2050 guidelines, and efficiency measured as the lowest GWP per kg energy corrected milk (ECM) leaving the farm.

In all seven years LFS was found to be the most efficient system ( $\mu=0.80 \text{ kgCO}_2\text{e kgECM}^{-1}$   $\text{sd}=0.04$ ) and HFC the least ( $1.17 \text{ kgCO}_2\text{e kgECM}^{-1}$   $\text{sd}=0.14$ ). Average LFS milk yield was 48% higher than HFC, and annual yields differ by ~3500kg across systems, therefore productivity was a key factor. The influence of both forage and genotype were found to be significant ( $P<0.001$ ) and year was not significant. Overall LF was more efficient than HF and S more efficient than C. Enteric CH<sub>4</sub> made the highest contribution to GWP of all systems (48-50%) followed by emissions from animal wastes (24-30%). Net CO<sub>2</sub> emissions were higher in LF, reflecting greater energy use and imported feeds. However, N<sub>2</sub>O emissions were higher in HF, owing to increased land and fertiliser use, greater waste excreted nitrogen per cow and the higher emissions factor for deposition of animal wastes at pasture. N<sub>2</sub>O emissions from HFC were double those from LFS per unit milk. Despite gross emissions being higher per cow from LF systems, increased milk production in LF groups resulted in lower GWP per unit ECM.

The results of the study showed that interaction between forage and genotype significantly influenced the GWP in dairy production. Although CH<sub>4</sub> emissions made the highest contribution to GWP, it was farm productivity and N<sub>2</sub>O emissions from fertiliser and excreta that were key factors. High enteric CH<sub>4</sub> increased CO<sub>2</sub> emissions associated with production/delivery of feeds and energy for LF systems were offset by the high productivity of intensive systems. Conversely, high nitrous emissions associated with conventional grazing HF systems were not offset by increased productivity and were thus less efficient.

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# EFFECT OF FORAGE REGIME AND CATTLE GENOTYPE ON THE GLOBAL WARMING POTENTIAL OF DAIRY PRODUCTION SYSTEMS

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## ABSTRACT

The aim of this study was to assess by Life Cycle Analysis (LCA) the effect of forage regime and cattle genotype on the global warming potential (GWP) of dairy production systems within a conventional farm. The study was based on four dairy systems established in Scottish Agricultural College's (SAC) long-term Holstein-Friesian genetic and management systems project. Two forage regimes (high forage (HF) and low forage (LF)) were applied to each of two genetic lines (select (S) and control (C)) giving four contrasting production systems (HFS, HFC, LFS and LFC). The HF group received 85% of their diet from home grown forages (rye grass, wholecrop wheat, wholecrop maize) and grazed pasture when available, while LF group were fully housed and received 55% of their ration from purchased concentrates. Select group represented top 5% UK genetic merit for milk fat and protein, while Control group were of average UK genetic merit. Using Tier 3 LCA methodology<sup>(1)</sup> efficiency of each system was measured for each of seven years (2004-2010) in terms of kgCO<sub>2</sub>-equivalents per kg of energy corrected milk (ECM) leaving the farm, and kgCO<sub>2</sub>-equivalents per hectare (ha) productive farmland. The effects of forage regime and genotype and their interactions were determined using analysis of variance applying a general linear model. Relative systems efficiency was evaluated by rank correlation.

In all years LFS (lsmean=0.94 kgCO<sub>2</sub>e kgECM<sup>-1</sup>, s.e.m=0.02) was found to be the most efficient system (P<0.001) per unit ECM and HFC the least (lsmean=1.35, s.e.m=0.02). Using ECM as a functional unit, LF was more efficient than HF and S more efficient than C. Average LFS milk yield was 48% higher than HFC and annual yields differed by ~3500kg cow<sup>-1</sup> across systems, therefore productivity was a key factor. When using area of farmland as a functional unit, S was still more efficient than C but HF more efficient than LF. HFS was the most efficient system (P<0.001) per unit farmland (lsmean=13331 kgCO<sub>2</sub>e ha<sup>-1</sup>, s.e.m=881) and LFC the least (lsmean=19099, s.e.m=1004). Main effects of both regime and genotype on GWP were significant (P<0.001) but there was no significant interaction between these factors. Enteric CH<sub>4</sub> made the highest contribution to GWP of all systems (50-57%). Contribution of embedded emissions in imported feeds and bedding was higher in LF, while emissions associated with fossil energy, inorganic fertilisers and animal wastes were higher in HF.

Improving genetic merit of the dairy herd lowered both GWP per unit ECM and GWP per hectare of farmland. Fully housed system was found to lower GWP per unit ECM.

**References:** <sup>(1)</sup> Intergovernmental Panel on Climate Change. 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*

**Keywords:** Dairy, Milk, Forage, Genotype, Greenhouse Gas, Emissions, Global Warming, Life Cycle Analysis

# EFFECT OF FORAGE REGIME AND CATTLE GENOTYPE ON THE GLOBAL WARMING POTENTIAL OF DAIRY PRODUCTION SYSTEMS

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**Abstract** The aim of this study was to assess by Life Cycle Assessment (LCA) the effect of forage regime and cattle genotype on the global warming potential (GWP) of conventional dairy production systems. Two feeding regimes (low forage vs high forage) were applied to each of two genetic lines (Control and Select genetic merit for milk fat and protein), giving four contrasting production systems assessed over seven years. Key factors in the difference between systems were high off-farm gross CO<sub>2</sub>e emissions in the low forage regime (due to feed imports) and high N<sub>2</sub>O emissions in grazing systems (owing to increased land, fertiliser, excreted nitrogen and deposition at pasture). Higher gross emissions in low forage group and Select genetic line were offset by high productivity. Improving genetic merit of the dairy herd and implementing the low forage system both lowered GWP per unit ECM.

**Keywords:** Dairy, Forage, Genotype, Greenhouse Gas, Life Cycle

**1. Introduction** Dairy production systems are an important contributor of anthropogenic greenhouse gas (GHG) emissions. Components of the total GWP of dairy production systems arise from processes both on and off the farm. These include enteric methane (CH<sub>4</sub>) direct from livestock, emissions from liquid and solid animal wastes, agricultural soils and from decomposition of crop residues. In addition, GHG are also emitted in the external production and transport of animal feeds and inorganic fertilisers. If the dairy industry is to meet the growing global demand for dairy products, ways to minimise GHG emissions per unit product in a sustainable way will become increasingly important. Increasing the efficiency of livestock production through animal breeding and nutrition are some of the most promising ways to reduce GHG emissions (Steinfeld et al 2006). It has been shown that high yielding dairy cows with high feed intakes are associated with a lower enteric CH<sub>4</sub> output per unit milk (Bell et al 2010), therefore herd numbers may be optimised for level of production. Chagunda et al (2009) showed that although increasing milk production was associated with a reduction in enteric CH<sub>4</sub> per unit milk, excreted waste nitrogen could increase both per unit milk and per hectare land used depending on the genetic merit of animals and the specific details of the production system. Therefore the overall GHG pollution potential from dairy production systems is dynamic process which should be assessed at a whole systems level in order to optimise the total output of pollutants against productivity. The aim of this study was to assess by way of LCA the effect of forage regime and cattle genotype on the GWP of dairy production systems within a conventional farm.

**2. MATERIAL AND METHODS** The study was based on Scottish Agricultural College's (SAC) established long-term Holstein-Friesian genetic and management systems project, situated at SAC Dairy Research Centre, Crichton Royal Farm, Dumfries. Data used were collected over the period January 2004 to December 2010, and incorporated specific details of four distinct systems within a conventional farm. Animals were maintained in two feeding groups, high forage (HF) and low forage (LF). The HF systems aimed to provide 75% by dry matter of the herd's mixed ration diet from home grown crops (ryegrass silage, whole crop maize, wheat alkalage) and 25% of ration composition coming from purchased concentrated feeds (distillers grains, rapeseed meal). Cows in the HF systems were turned out to graze

ryegrass pasture when available, and therefore the total home grown element of the annual HF diet was nearer to 85%. In contrast, the LF systems were fully housed; the herd retained indoors all year round and fed a diet of approximately 45% home grown forages, with 55% of diet from purchased concentrates (wheat, sugar beet pulp, soya) imported onto the farm. Within each forage system, animals comprised two contrasting genetic lines. Control (C) animals were bred to be of average UK genetic merit for milk fat and protein production, and Select (S) animals represented the top 5% of UK genetic merit. Maintaining the specific details of these groups in a long term genotype x feeding regime project resulted in four divergent dairy production systems – HFC, HFS, LFC and LFS. These systems are representative of the interaction between forage regime and genetic line. Cows were milked three times daily, received equal treatment regarding health and fertility, and herd numbers maintained at approximately 50 cows in each system. S and C cows were managed together and groups retained in the same building when housed. All young stock were managed together.

**2.1. Life Cycle Assessment** LCA stands today as the pre-eminent tool accounting for environmental impacts of products and their processes within a specified boundary. The systems under this study covered the life cycle required for the production of raw milk, from the on- and off-farm production of system inputs, to product leaving the farm-gate. On-farm system inputs included herd dynamics, productivity, energy, application of inorganic fertilisers, land use, cropping and feed intake. Off-farm inputs included the cost of production and transport of inorganic fertilisers, imported concentrated animals feeds and bedding. Impact assessment was conducted using a modified version of SAC Carbon Calculator vII (RBU 2011), designed specifically for use in the Scottish agricultural sector and implementing IPCC Tier II methodology (IPCC 2006). Liaising closely with the developer, this study was able to implement Tier III methodology in order to properly define specific differences among the four dairy production systems. GWP, the environmental impact category for this study, was expressed in terms of kgCO<sub>2</sub>-equivalents. The primary function of dairy systems is milk production, therefore the functional unit (FU) chosen to reference the GWP was “1 kg of energy corrected milk (ECM) leaving the farm gate”. A breakdown of system component contributions to the GWP per kgECM is displayed in table 1. Total area of farm land in hectares (ha) required to fulfil each system was also assessed as a second FU for relative systems efficiency.

**2.2. Statistical Analysis** Relative efficiency of systems was assessed using analysis of variance (ANOVA). The most efficient system was determined as having the lowest GWP per FU. The general linear model used to assess effects of forage regime and genotype on GWP

*Table 1. Descriptive statistics for components of Life Cycle Assessment output, expressed as kg carbon dioxide equivalents per kg energy corrected milk (kgCO<sub>2</sub>e kgECM<sup>-1</sup>)*

Component	LFC		LFS		HFC		HFS	
	mean	sd	mean	sd	mean	sd	mean	sd
Fossil fuels	0.06	0.01	0.05	0.01	0.06	0.01	0.05	0.01
Electricity	0.03	0.00	0.03	0.00	0.03	0.00	0.03	0.00
In. fertiliser production	0.06	0.01	0.05	0.01	0.09	0.03	0.08	0.02
Purchased feed & bedding	0.19	0.01	0.16	0.01	0.16	0.01	0.14	0.01
Enteric fermentation	0.54	0.02	0.45	0.03	0.64	0.04	0.53	0.04
Animal wastes CH <sub>4</sub>	0.06	0.02	0.06	0.02	0.09	0.01	0.08	0.01
Animal wastes N <sub>2</sub> O	0.09	0.00	0.08	0.01	0.16	0.02	0.13	0.01
In. fertiliser application	0.04	0.01	0.04	0.01	0.07	0.02	0.06	0.02
Crop residues	0.04	0.00	0.03	0.00	0.05	0.00	0.05	0.00
Milk yield (kgECM cow <sup>-1</sup> )	9246	800	10753	853	7281	533	8189	656
Farmland required (ha cow <sup>-1</sup> )	0.52	0.08	0.60	0.08	0.73	0.11	0.76	0.12



was:  $y_{ij} = \mu + G_i + F_j + (G \times F)_{ij} + Y_{ij} + \varepsilon_{ij}$  where  $y_{ij}$  is the total global warming potential of the dairy production system per kg ECM and per hectare farmland;  $\mu$  is the overall mean;  $G_i$  is the fixed effect of genetic line (Control or Select);  $F_j$  is the fixed effect of feeding system (Low Forage or High Forage);  $(G \times F)_{ij}$  is the effect of interaction of forage and genetic line;  $Y_{ij}$  is the fixed effect of calendar year;  $\varepsilon_{ij}$  is the random error term. All statistical analysis was conducted using Minitab 16.

**3. Results and discussion** In all years LFS was found to be the most efficient system per unit milk ( $P < 0.001$ ). The HFC system, representative of a typical UK dairy farm, was found least efficient in all years. Results from ANOVA are presented in table 2. Average LFS milk yield was observed to be 48% higher than HFC, therefore productivity was a key factor. Using ECM as a functional unit, the total overall GWP was found to be 18% lower in LF and 14% lower in S groups. Effect of both forage regime and genotype on the overall GWP were found to be highly significant ( $P < 0.001$ ). The interaction term was not found to be significant. The results suggest that there is potential to reduce the GWP per unit productivity of a typical conventional UK dairy system by up to 30%. Improving the herd genetic merit could potentially bring 14% reduction in the GWP per unit productivity. Improvement necessarily proceeds gradually and would realistically take several years to return results. Results also suggest that switching to the low forage system holds potential for a reduction in GWP of up to 18% per unit productivity. When using area of farmland as a functional unit, the effect of forage regime on total GWP was found to be significant ( $P < 0.001$ ). HF was found to be more efficient than LF but S was not significantly different to C. HF groups required an additional  $0.18 \text{ ha cow}^{-1}$  ( $\text{sd}=0.06$ ) land annually due to grazing. HFS was the most efficient system ( $P < 0.001$ ) per ha farmland and LFC least.

$\text{CH}_4$  made the highest contribution to GWP of all systems (50-57%). Although gross enteric  $\text{CH}_4$  was found to be 7% less per cow in HF, when referenced to productivity the GWP of enteric  $\text{CH}_4$  from HFC was around 40% higher than LFS. Under the fully housed regime, 100% of the milking herd excreta was stored under anaerobic conditions as liquid slurry, resulting in higher gross manure  $\text{CH}_4$ . Despite this LF groups were still observed to be more efficient in terms of manure  $\text{CH}_4$  per unit ECM. In all groups,  $\text{N}_2\text{O}$  emissions were greatest from excreta, followed by emissions from inorganic fertilisers and thirdly from crop residues. The contribution of  $\text{N}_2\text{O}$  from inorganic fertilisers was lower than expected. This can be explained by a comparatively low application rate of inorganic nitrogen ( $87 \text{ kg N ha}^{-1}$ ,  $\text{sd}=22$ ), resulting from more efficient use of fertilisers by implementing slurry injection. Gross emissions relating to the application of inorganic fertilisers were higher for the outdoor HF systems, owing to additional grassland requiring management for grazing. Gross nitrous emissions from animal excreta were also considerably higher from the HF systems, owing to

*Table 2. Least squares means for global warming potential per kg energy corrected milk and per hectare farmland of forage regime, genetic line and dairy production systems*

Variable	Level	kgCO <sub>2</sub> e kgECM <sup>-1</sup>	kgCO <sub>2</sub> e ha <sup>-1</sup>
Forage regime	Low (LF)	1.02 <sup>a</sup>	18595 <sup>a</sup>
	High (HF)	1.25 <sup>b</sup>	13691 <sup>b</sup>
	sem	0.016	616.2
Genetic line	Control (C)	1.23 <sup>a</sup>	16575
	Select (S)	1.05 <sup>b</sup>	15711
	sem	0.016	616.2
System	LFC	1.10 <sup>a</sup>	19099 <sup>a</sup>
	LFS	0.94 <sup>b</sup>	18091 <sup>a</sup>
	HFC	1.35 <sup>c</sup>	14051 <sup>b</sup>
	HFS	1.15 <sup>a</sup>	13331 <sup>b</sup>
	sem	0.023	871.5

Different superscripts within a column denote significant differences between levels of same variables ( $P < 0.001$ )

greater waste excreted nitrogen per cow and an emissions factor 20 times higher for deposition of animal wastes at pasture compared with liquid storage (IPCC 2006). When referenced against productivity, HFC produced double the N<sub>2</sub>O from animal wastes compared with LFS and 59% higher emissions from applied inorganic fertiliser. Quantities of home-grown forage crops required by all systems were broadly similar, thus emissions associated with crop residues were comparable across all groups. However, increased productivity of LF again led to lower GWP per unit milk. Contribution of embedded emissions in imported feeds and bedding was 48% proportionally higher in LF. However, this is in line with what would be expected of a fully housed system, as opposed to the grazing groups which spent an aggregate 148 (sd=15.5) full days at grass annually. The imported feed and bedding component of the systems' GWP dynamic was the only contributing category to remain higher in LF than HF when referenced to milk production. As with the associated N<sub>2</sub>O emissions, the embedded CO<sub>2</sub>e in imported inorganic fertilisers were lower in LF groups owing to increased fertiliser requirement of the grazing system. Gross emissions were 27% lower in LF and the margin widened when referenced to kgECM.

**4. Conclusion** Key factors in the difference among systems were high off-farm gross CO<sub>2</sub>e emissions in LF and high on-farm N<sub>2</sub>O emissions in HF. In LF groups high gross emissions were offset by high productivity but this was not the case for the more extensive HF groups. Main effects of both forage regime and genotype were found to be individually significant when GWP referenced to productivity. Improving genetic merit of the dairy herd and implementing low forage system both lowered GWP per unit ECM.

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